Pooja Singh · Rajeev Pratap Singh
Vaibhav Srivastava *Editors*

Contemporary Environmental Issues and Challenges in Era of Climate Change

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Dedicated with affection to Our Parents,
Teachers, and Family Members for their
constant encouragement and support

Climate change increasingly poses one of the biggest long-term threats to investments

Christiana Figueres

The proper use of science is not to conquer nature but to live in it

Barry Commoner

Preface

The last few decades have witnessed the prodigious population growth worldwide that led to increased demand for food and shelter. Consequently, extraction of the natural resources beyond the resilient capacity of the Earth is being performed that results in a devastating effect on ecosystems and environmental health. Presently, climate change is of prime concern among the scientific community as it is not only impacting the current world population but will also have a disastrous impact on future generations. Climate change has a significant impact on global hydrological cycle, ecosystems functioning, coastal vulnerability, forest ecology, food security, agricultural sustainability, etc. Therefore, there is a need for judicious management of natural resources and comprehensive and preventive policy approaches such as adoption of renewable energy and climate resilient agriculture, which would help in reverting the impairment due to human-induced climate change. According to the Intergovernmental Panel on Climate Change (IPCC), only immediate and sustained action will stop climate change from causing irreversible and potentially catastrophic damage to our environment. With this background, the present book attempts to accommodate different scientific views and concepts, researches, reviews, case studies, etc. on contemporary environmental issues under changing climate scenarios and different adaptation measures. This book raises an alarm on the modern-day pattern of climate alteration and, therefore, will facilitate to tackle doubts of environmental scientists, researchers, policymakers, and common people.

Chapter 1 entitled “Ecosystem health and dynamics: An indicator of global climate change” by Gini Rani and others explains the impacts of climate change on the health of various aquatic and terrestrial ecosystems. The detrimental effects, short- and long-term responses like changes in physiology, phenology, and life cycle of organisms, loss of productivity, and loss or migration of species have also been elaborated in detail for every single ecosystem.

Chapter 2 entitled “A comprehensive evaluation of heavy metal contamination in foodstuff and associated human health risk: A global perspective” by Saahil Hembrom and others gives an overall review of heavy metals contamination in foodstuff and its health risk-related issues from a global perspective. Also, different preventive and mitigation measures are nicely explained.

Chapter 3 entitled “Climate change impact on forest and agrobiodiversity: A special reference to amarkantak area, madhya pradesh” by Bhairo Prasad and others highlights the impact of climate change on the forest and agro-biodiversity of Amarkantak region. The study suggests that low average rainfall and rising mean temperature are negatively correlated with the forest and agro-biodiversity in this region.

Chapter 4 entitled "Agricultural sustainability and climate change nexus" by Deepika Pandey focuses on the ramifications of climate change in particular of agricultural sustainability. The author attempts to establish a nexus approach between climate change and agricultural sustainability in a meticulous manner.

Chapter 5 entitled "Heat stress in crops: Driver of climate change impacting global food supply" by Richa Rai elucidates the factor responsible for the rise in temperature and its role in enhancing the frequency of drought and salinity episodes which also affects agriculture production and response of increased temperature on crops phenology, physiology, and productivity.

Chapter 6 entitled "India's major subsurface pollutants under future climatic scenarios: Challenges and remedial solutions" by Pankaj K. Gupta and others offers the state-of-the-art knowledge on challenges and issues related to India's major pollutants under current and future climatic scenarios. The chapter improves our understanding of the behaviors of several major pollutants including As, F, nitrate, hydrocarbons, and salinity under future climatic scenarios. Also, this chapter facilitates to frame and implement remediation and management of major Indian subsurface pollutants under different climatic conditions.

Chapter 7 entitled "Phosphorus sorption characteristics of the surface sediments from industrially polluted GBPS reservoir, India" by Bijendra Kumar and Anshumali analyzed phosphorus sorption kinetics and equilibrium isotherm, and the relationship between phosphorus sorption parameters in 24 industrially contaminated surface sediments of Govind Ballabh Pant Sagar (GBPS) reservoir, India.

Chapter 8 entitled "Spatiotemporal variations of precipitation and temperatures under CORDEX climate change projections: A case study of Krishna river basin, India" by Shaik Rehana and others demonstrates the use of bias-corrected Coordinated Regional Downscaling Experiment (CORDEX) model simulation in analyzing the regional scale climatology at the river basin scale, Krishna River Basin (KRB), India. The precipitation and temperature simulations from CORDEX models with Representative Concentration Pathways (RCP) 4.5 were evaluated for the historical data for the period of 1965 to 2014 with India Meteorological Department (IMD) gridded rainfall and temperature data sets cropped over the basin and projections were made.

Chapter 9 entitled "Microorganisms in maintaining food and energy security in a world of shifting climatic conditions" by Nikita Bisht and Puneet Singh Chauhan provides a good account of microbial ecology for climate change adaptation and mitigation to ensure food and energy security under shifting climate scenario in a multifaceted way.

Chapter 10 entitled "Engineering photosynthetic microbes for sustainable bioenergy production" by Amit Srivastava and others gives an overview of the approaches for strain/process developments through genetic engineering, optimization of bioreactors, and processing technology that may pave the route to produce biofuels that can guarantee global energy retreat in a sustainable fashion.

Chapter 11 entitled "Ensuring energy and food security through solar energy utilization" by A.K. Singh and others focuses on harnessing solar radiation to ensure energy and food security. The chapter provides information of different solar energy operated machineries that can be used in various agricultural applications. Also, solar energy can potentially be used for electricity generation from an agri-voltaic system, which further reduces our dependence on coal-fired power plants.

Chapter 12 entitled "A conceptual framework to social life cycle assessment of e-Waste management: A case study in the city of Rio de Janeiro" by Leonardo Mangia Rodrigues and others explains and analyzes the social impacts of the solid waste management specifically regarding the Waste Electrical and Electronic Equipment (WEEE) in the city of Rio de Janeiro, Brazil. This chapter briefly presents how the reverse logistics contributes to a closed-loop supply chain based on the Life Cycle Thinking philosophy, as well as its crucial role towards the Circular Economy by promoting sustainable practices of handling products in their end of life phase, thus a sustainable solid waste management through reuse and recycling strategies.

Chapter 13 entitled "Unsustainable management of plastic wastes: A threat to global warming and climate change" by Amit Vishwakarma highlights the issue of solid waste management particularly plastic wastes around the globe and how it has become a new emerging source of greenhouse gas (GHG) emission. Also, different management approaches have been discussed in an elegant manner.

Chapter 14 entitled "Assessment of public acceptance of the establishment of a recycling plant in Salfit district, Palestine" by Majd M. Salah and others aims at assessing the public acceptance of Reduce–Reuse–Recycling (3R) principle in Salfit district, Northern West Bank, Palestine.

Chapter 15 entitled "An overview of the technological applicability of plasma gasification process" by Spyridon Achinas offers an overview of plasma-based gasification (PG) technology, a survey of existing PG facilities, a comparison with other thermal techniques, and an identification of its environmental impacts. PG is a thermochemical process whereby wastes are converted into valuable energy in the form of gaseous fuel (syngas) that can be used for heat, power, or biofuels production.

Chapter 16 entitled "Natural gas hydrates: Possible environmental issues" by Sotirios Nik and others gives us a better understanding about natural gas hydrates. Presently, the gas hydrates are known as a potential source of methane that when released to the atmosphere causes more global warming than carbon dioxide, which is the reason for ocean acidification. The chapter suggests that natural gas hydrates may also be considered as a promising future energy source.

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Our special thanks to the almighty God for giving us strength and courage and also for giving us this opportunity.

Varanasi, Uttar Pradesh, India

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Dr. Rajeev Pratap Singh is an Assistant Professor at the Institute of Environment and Sustainable Development (IESD), Banaras Hindu University, India. He completed his Ph.D. at the same University. His main research interests include solid waste management, bio-composting, and green technologies. He has received several international awards, including the "Green Talent" award from the Federal Ministry of Education and Research (BMBF), Germany; Prosper.Net Scopus Young Scientist award, and DST Young Scientist Award. Dr. Singh is a member of the reviewer and editorial teams of several leading scientific journals, has edited 5 books, and published 50 highly cited research and review articles on solid waste management. Dr. Singh also received a Water Advanced Research and Innovation (WARI) Fellowship from DST, Govt. of India, IUSSTF, University of Nebraska-Lincoln (UNL), and the Robert Daugherty Water for Food Institute (DWFI).

Dr. Vaibhav Srivastava has completed his doctoral research at the Institute of Environment and Sustainable Development (IESD), Banaras Hindu University, India and M.Sc. in Botany from the University of Allahabad, India. His research interests include solid waste management, composting and vermicomposting, ecotoxicology and sustainable agricultural practices. He is a life member of the Indian Science Congress Association (ISCA), Kolkata, the Indian Botanical Society, Bareilly, the International Society of Environmental Botanists (ISEB), Lucknow, and Prof. H.S. Srivastava Foundation for Science and Society, Lucknow and annual member of the Society of Environmental Toxicology and Chemistry-Asia Pacific, United States. He published 14 scientific articles in respected international journals/books and edited a book with IGI Global, Hershey, PA, USA till date. He is currently serving as a reviewer for various international journals.

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Ecosystem Health and Dynamics: An Indicator of Global Climate Change

1

Gini Rani, Jaskiran Kaur, Ajay Kumar, and K. N. Yogalakshmi

Abstract

Climate change is perhaps one of the major critical problems of recent times. It has become a subject of international concern since its increase at an alarming speed. Although atmospheric gases, surface solar radiations, volcanic activity, cosmic rays and alterations in earth's orbit are targeted as the potential causes of climate change, their consequences or impacts are not well documented. Sea level rise, flooding, extreme weather patterns, heat waves and drought are some of the pronounced consequences of climate change. Changes in biodiversity, ecosystem and ecosystem services and health caused by climate change have received minimal attention. A healthy ecosystem requires a wide diversity of microorganisms, plants and animals at different trophic levels. Removal of a single species from the niche or introduction of an invasive species might lead to ecosystem destruction. Abnormal changes in the climate pattern can alter the ecosystem health through loss of species, extinction of species, migration of species and changes in behavioural pattern. However, these changes are invisible till a species get extinct or endangered. Further the change in ecosystem health due to alterations in climate is difficult to record unlike other impacts. Sustainable practices that can reduce, sequester or capture the greenhouse gas emissions may halt the biodiversity loss, protect the ecosystem from further destruction and restore them. This chapter comprehensively describes the impacts of climate change on the health of various aquatic and terrestrial ecosystems. The detrimental effects, short- and long-term responses like changes in physiology, phenology and life cycle of organisms, loss of productivity and loss or migration of species have also been elaborated in detail for every single ecosystem.

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Climate change · Biodiversity · Ecosystem health · Loss of species · Aquatic · Terrestrial · Ecosystem

1.1 Introduction

According to the World Meteorological Organization (WMO), climate in an area can be depicted by statistically analysing (mean conditions) physical atmospheric variables such as precipitation, ambient temperature, wind, seasonal cycles and weather extremes occurring over a period of 30 years. The classical time period of three decade is considered as an indicator for studying cumulative weather pattern (climate). Climate system is an interaction of five chief components including the hydrosphere, lithosphere, atmosphere, biosphere and cryosphere. They develop under the stimulus of internal dynamics, external forcing (volcanic activities and solar variations) and anthropogenic interferences such as changes in land use pattern. The climatic structure is affected by the forces from outside the earth such as rotation of the earth, solar insolation, geometry between the sun and earth and gradual changing of the earth's orbit. In response to these stimuli over a period of time, the physical and chemical nature of earth change. The phenomena such as continental drift, land erosions, shifting of oceanic floor and change in water vapour result in change in climate.

The constituents of the atmosphere are crucial in shaping the climate of an area. Nitrogen, oxygen and argon are permanent gases and constitute 99.9% of the total atmospheric gases. The other fraction of the gas (0.1%) is constituted by carbon dioxide, nitrous oxide, methane, oxide and surface level ozone, which despite being in trace amount have a strong effect on the earth's energy budget. These climate pertinent gases along with water vapour absorb solar radiation emitted from the earth's surface and reradiate it back to the surface of the earth causing greenhouse effect, and the gases are named greenhouse gases. The major changes in the composition of the atmosphere are caused by natural phenomena which include water in different forms such as cloud of liquid water/ice crystal, hail, permafrost, snow and rain. A change in any single component of the climate system causes change in the entire climate system.

Human activities such as indiscriminate combustion of fossil fuel and deforestation are emerging factors which has strengthened greenhouse effect inducing climate change. Most of these activities have pronounced effect similar to natural forces. Land use changes including deforestation for expanding agricultural land area and road and building construction are some of the factors affecting climate. Deforestation and fossil fuel combustion have resulted in slow buildup of atmospheric GHGs, changing the composition of atmospheric gases by interfering with the solar radiation. Since the advent of the industrialization, atmospheric CO_2 level has increased by 30% (Trenberth and Fasullo 2013). The concentration of CO2 is projected to increase two folds in next 100 years if the relentless deforestation and industrial release is not controlled. Urban heat island is a very common phenomenon of local climate change arising from usage of electrical/electronic appliances, burning of fossil fuel and industrial release of toxic gases. In contrast to urban heating, a cooling effect known as suburban cooling effect has also been observed.

Aerosols of size less than 1 μm play an important role in influencing climate. The natural processes that induce aerosols are wind in desert and eruption in mountains. The anthropogenic source of aerosols are power plants and burning of biomass. While aerosols directly absorb sunlight causing enhanced warming, sometimes it reflects some radiation back into the space, causing cooling effect. The absorption and reflection of sunlight by clouds are mainly determined by the aerosols because it acts as nuclei around which the water droplet condenses and forms cloud. When sulphur dioxide (SO_2) from industrial plume is released into the atmosphere, it gets oxidized and get transformed into sulphate aerosols. The sulphate aerosols are responsible for the appearance of milky haze over the land surface.

The global warming affects oceans and causes melting of ice caps. The increasing level of CO_2 alters the chemical nature of oceans, which ultimately affect the ecosystem. Atmospheric warming increases the temperature of oceans and decreases its salinity. The melting of ice caps causes sea level rise which largely affects coastal and offshore habitat, as mentioned in Fig. 1.1. The pressure put by the driving forces have negative impact on the flora and fauna of that habitat. Recurring drought can

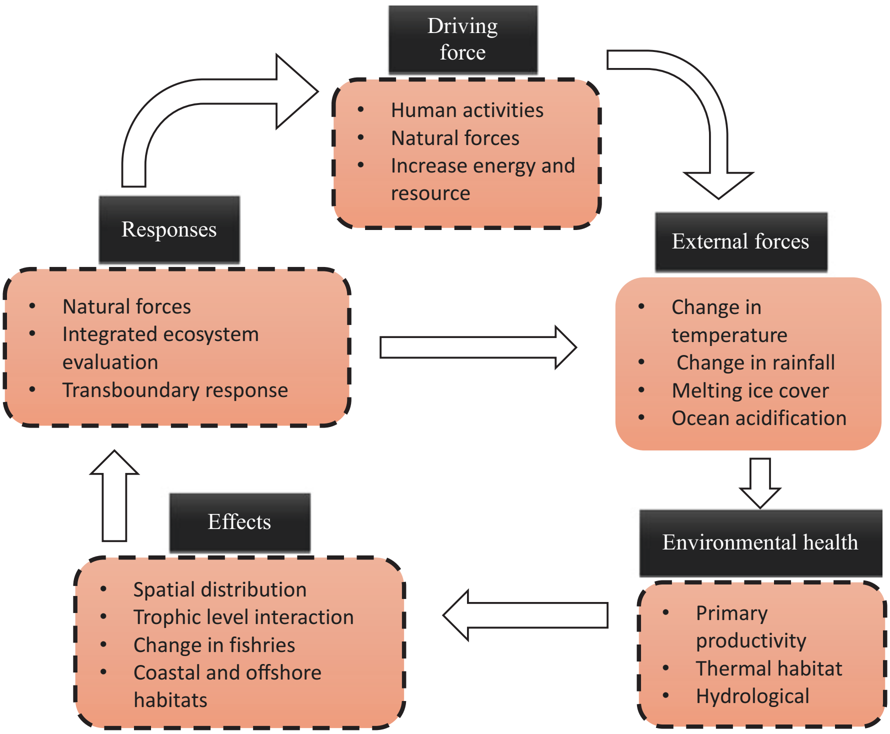

Fig. 1.1 Forces leading to change in different components of ecosystem and its effect in the climate system

trigger frequent forest fires destroying numerous species. Global warming resulted by climate change is supposed to cause extinction of vulnerable species because the rate of climate change is more rapid for the species to be able to adapt to the changing climate. The population of Himalayan snow leopards has been assumed to have declined by around 20% in the last two decades. This is mainly because of disruption and fragmentation of habitation mediated by climate change and illegal poaching. This holds true for the population of tigers too, which has reduced to mere 3200 only.

Oceans are supposed to be largest carbon sinks, which help in maintaining atmospheric CO_2 level. However, rising temperature and increased concentration of CO_2 than normal level make ocean acidic. In present scenario, large-scale change is observed in marine habitat at temperature of 1 °C. At projected increase in temperature of 1.5 °C, coral reefs are suspected to decline by 70–90%. Likewise, the climate change shows both short- and long-term impacts on ecosystem resulting in loss, migration and change in the living habits of plants, animals and even microorganisms. The detailed impact of climate change on different ecosystems will be discussed in the forthcoming sections.

1.2 Climate Feedback to Ecosystem Health and Dynamics

The influence of long-term changes in temperature, rainfall, humidity and clouds on the plant and animal productivity and ecosystem heath is discussed in detail for different ecosystems.

1.2.1 Terrestrial Ecosystem

Terrestrial ecosystems are characterized by the interaction of biological and physical component present on the land surface (Mirkhani et al. 2009). They are also termed as land-based ecosystems. The interwoven network of biological community with the physical entities on the continents and islands are called as terrestrial ecosystem. Terrestrial ecosystem is formed by the combined effect of different natural physical processes such as nutrient cycles; earthquakes and volcanic activity; flow of river, ice and sediments; and many others. The occurrence of tectonic forces such as earthquake and volcanoes certainly reshapes existing ecosystem in remarkable ways by modifying the spatial distribution of the ecosystem services. During the vibrations of landmasses and eruption of hot lava, carbon storage function, soil preservation and water withholding capacity get altered. A huge destruction, alteration and shift in the biological community also occur during such natural disasters. Terrestrial ecosystems tend to have higher thermal fluctuations compared to aquatic ecosystems on daily and seasonal basis (McNaughton 2014). Moreover, light and gases are abundantly available in terrestrial ecosystem compared to aquatic ecosystem due to the transparency. Light and gases play a central role in vital processes, for instance, CO_2 in photosynthesis, O_2 in aerobic respiration and N_2 in nitrogen fixation.

Terrestrial ecosystems are of four major types: forest, grassland, mountain and desert ecosystem. These ecosystems are invariably influenced by the existing climate. Climate is an important factor that influences the formation and interaction of terrestrial ecosystem. The ecosystem responses to the climatic variation are extensively complicated due to a number of reasons. The implications of different individual feedbacks are usually suppressed or amplified by several other mechanisms that occur on broader range of spatial and temporal level having different repercussions on different levels, and they possibly influence various aspects of climate extending from local rainfall intensity to worldwide scale temperature, and more importantly they are closely involved with human activities as inducers and responders (Field et al. 2007). The principle mechanisms involved in the climate feedback of terrestrial ecosystem are by either magnifying or suppressing climate forcing which comprise (1) changing concentration of atmospheric GHGs (greenhouse gases) such as CH_4, CO_2 and N_2O and (2) changing absorption or distribution of net solar irradiance in different layers of the atmosphere or on the earth's surface. The change in radiative forcing leads to either positive feedback loops or negative feedback loops. The climate change feedback to different terrestrial ecosystems is elaborated in the forthcoming sections.

1.2.1.1 Forest Ecosystem

Around 30% of the earth's land surface is covered under forest area. Forest cover is characterized by huge biodiversity and resources which provide a wide range of ecosystem services including ecological, social, economic and aesthetic services to humans and other natural systems. As forest resources are renewable in nature, humans since ancient times have relied on forests for fuel wood, shelter, medicines, food and other forest products. Additionally, forests play a key role in major ecological functions. It is not only responsible for the protection of soil but formation of most of the soil on the earth. Soil is nothing but disintegrated rock mixed with dead parts of plants and community of microorganisms. Forests help in the regulation of hydrological cycle as they uptake water and release it into the atmosphere through transpiration process and release it in the soil as liquid excretion. They maintain water supply by storing water like natural sponge. When rainfall occurs, it falls on the canopy of the tress rather than directly hitting the ground, thus saving from land erosion. The water is absorbed by roots and transported through the trunks and branches to the leaves. The excess water is released into the atmosphere through the leaves. When sufficient moisture is transpired by the leaves into the atmosphere, clouds are formed and precipitation occurs, and similarly cycle repeats as such. Forests help in maintaining nutrient/mineral cycle as forests take up nutrients from soil and return it in the form of dead leaves, which form rich humus. Forest influences climate at large by exchanging different gases, water and chemicals. Carbon cycle is a crucial aspect in understanding climate and its feedback in forest ecosystem. Around 33% of total anthropogenic carbon emission including fossil fuel combustion and land use change was reported to be sequestered by forest (Solomon et al. 2007). In general, forest utilizes around 2.6 GtC/year (Norby et al. 2005). The terrestrial net primary productivity (~50%) from forest is more than its carbon storage (~45%). In response to rising CO_2 level, plants can create either negative climate feedback in which warming is decreased or positive feedback which amplifies warming. Climate models (terrestrial and oceanic carbon cycle) suggest positive feedback mechanism between climate change and carbon cycle which increases anthropogenic CO_2 emission, thereby magnifying global warming (Friedlingstein et al. 2006). Increasing concentration of CO_2 triggers increased photosynthesis process and transpiration by plants, which increases atmospheric moisture and in turn more precipitation, which ultimately brings cooling effect. As part of negative feedback mechanism by plants, the increased CO_2 is dissolved in rainwater and is stored in sea and oceans.

According to multi-model analysis, rising airborne CO_2 increases carbon storage in the ecosystem causing 12–76% increase in net primary productivity (NPP) (Solomon et al. 2007). According to one of the reports, ~50% increase of atmospheric CO_2 level for over several years results in enhanced NPP by 23% (Norby et al. 2005). But in longer run, the outcome is different because of the interactions of other natural species and factors. The biogeophysical performance of forest is altered as ecological reaction to changing climate leading to climate feedback. These climate feedbacks consist of altered stomatal activity, leaf area index and composition of species. Rising atmospheric CO_2 decreases stomatal conductance which diminishes the rate of evapotranspiration leading to warming.

The implication of warmer climate would be lengthened growing season in plants and increased uptake of water and evaporation by plants causing condition of water stress in the soil. The jeopardy of drought would increase leading to reduced forest productivity and making trees vulnerable to insects and diseases. The predicted rise in temperature will bring changes in atmospheric moisture, snowfall and precipitation, which will invariably change water cycle. Snow cover is likely to diminish increasing water runoff. Climate change is expected to amplify the threat of invasive plant intrusion resulting in decreased productivity in forest.

The potential effect of changing climate on the wildlife would be change in physiology as well as population of native animals. Mammals are affected by climate change through change in food availability and shelter, direct thermal stress condition and infestation of parasites and disease. Brown bats are susceptible to change in hibernation condition and food resources. Change in vegetation and heat stress will affect many species of mammals. Amphibians are potentially sensitive to fluctuating ambient temperature and precipitation caused by climate change scenario because the breeding ground for most of the amphibians is standing water. Increased temperature and evaporation may lead to drought affecting breeding in amphibians.

Among other taxonomic groups, birds are focused much because several decades of studies on birds survey indicates significant change in the migration pattern, quality and number of habitat of birds in forest ecosystem and their abundance and distribution (Rustad et al. 2012). In response to climate change, a shift in earlier breeding and arrival of migratory birds have been observed. Birds that are restricted to high elevation forests and colder climate are much vulnerable to altered climatic conditions.

Climate change is also known to be linked to change in insects' range. Insects are base of many food webs and significant to biodiversity. Shift in the range of European butterflies has already been reported (Rustad et al. 2012).

With rising temperature, the structure of microbial community changes which speeds up the process of methanogenesis, respiration and fermentation. Climate change accelerates the process of organic matter degradation by microbes such as bacteria, archaea, fungi and algae. Increased microbial activity increases respiration rate and releases more CO_2 as waste product causing global warming. The enzymatic activity and physiology of microbes are directly affected by the climate change.

1.2.1.1.1 Tropical Forest

Tropical forest covers around the earth's 2 billion hectare of land area and is home to 13 million types of different species (70% of the earth's total flora and fauna). Most of these species of tropical forests are endemic (Anon 1996). Tropical rainforest forests play a central role in stabilizing the earth's climate. They influence local and global climate by absorbing atmospheric CO_2 and replenishing it with O_2. They also help in maintaining humidity. But the increasing population and ever-growing advancement have led to extensive deforestation. Agriculture, mining, dam construction, ranching and oil extraction are some of the major reasons for deforestation. Deforestation of tropical rainforest is the second most driver of climate change as it contributes in 18–25% of annual global CO_2 emissions. According to one of the recent reports published by the World Resources Institute, every year nearly 18 million hectares of forest is cut down (Graham et al. 2018). Throughout the 1990s, deforestation of tropical forest resulted in the emission of 0.9 to 2.2 GtC/year carbon dioxide (McCarthy et al. 2001; Eva et al. 2004). If deforestation of tropical forest is carried out with same pace as present scenario without any strict measures to prevent deforestation, then the emission of GHGs could reach 87 to 130 GtC/year by the year 2100 (Moutinho and Schwartzman 2005). These emissions are likely to accelerate because of logging, forest fires and tree mortality brought by drought. Moreover, the climate change is projected to alter forest ecosystem by changing mean ambient temperature and precipitation, along with extreme climatic conditions such as storms, droughts, wildfires and cyclones. This will ultimately bring alterations in the composition of forest and distribution of species, flowering and fruiting pattern and change in tree phenology in the long run (Butt et al. 2015). Natural phenomena such as El Niño which causes disruption in normal weather pattern due to changes in oceanic temperature (Pacific Ocean) distress the tropical rainforest by bringing in drought and heavy rainfall to different parts of the world. The events of El Niño are expected to double under the effect of climate change and may degrade forest ecosystem. According to Boulton et al. (2013), the Amazon forest suffered enormous degradation driven by drought events mediated by climate change. The outcome of global climate change is reported on life cycle pattern of plants (Bertin 2008). Out of all forest ecosystems, tropical forest has suffered greatest forest degradation in the last decade with yearly forest loss of 811.2 mi^2/year (Deb et al. 2018). The degree of tropical forest loss is massive in South America

(16% of total forest cover), while the rate of forest loss is highest in tropical Asia with 634.4 mi^2/year forest loss between the year 2000 and 2012 (Hansen et al. 2013). Climatic extremes are projected to affect tropical Asian forest by clearing 3/4 of its existing forest and decreasing its biodiversity to 50% by the year 2100 (Deb et al. 2017). The major reason of deforestation in tropical Asia is extensive conversion of forest cover into agricultural land. This accelerates susceptibility of tropical rainforest in Asia to the evident climate change. Forests innately release number of volatile organic compounds (VOCs) such as isoprene. These biogenic VOCs combine with different atmospheric gases and result into positive or negative radiative forcing following different indirect pathways. When biogenic VOCs rapidly react with atmospheric O_2, it increases the concentration of GHGs such as CH_4 and O_3, causing warming. In case of negative radiative forcing, the biogenic VOCs react with molecules in the atmosphere to form aerosol particles. These aerosols shift the compactness and the elevation of the clouds which scatter sunlight and increase the brightness of the clouds. In case of deforestation, less biogenic VOCs are released which leads to more warming effect. However, when the phenomenon of albedo is concerned, the dark green hue of the tropical forest has lower albedo as it absorbs relatively more sunlight and reflects less, compared to grasslands and crop land. Tropical deforestation leads to more albedo and negative radiative forcing, resulting to net global cooling (Shindell et al. 2013). But it is not yet clear as to whether warming brought by biogenic VOC interaction or cooling brought by increased albedo is pronounced.

1.2.1.1.2 Temperate Forest

The vegetation found in temperate forest ecosystem is by and large deciduous and evergreen trees. Broad leaved trees such as oak and maple generally dominate deciduous forest. These forests are found in Northeast Asia, Western Europe and Eastern North America. Climatic factors such as sunlight, water and nutrients are limiting factors for vegetation growth in the temperate forest. In temperate forest ecosystem, rainfall surpasses evaporation; therefore groundwater easily develops in areas having permeable substratum. The abundant precipitation forms shallow water table which influences the temperate vegetation to a large extent. Climate change causes change in precipitation which influences moisture content of the soil and ultimately affects the vegetation. Climate change, i.e. change in temperature, rainfall and CO_2 level, influences vegetation as well as hydrology of that area. In response to temperature rise, the phenology of deciduous trees is affected, and the altered phenology affects the hydrology. Increasing temperature extends growing season, influencing vegetation growth due to extension of carbon assimilation period and respiration. Change in the level of precipitation determines the availability of water for transpiration, interception evaporation, groundwater recharge and soil moisture, thereby limiting the growth of roots and water uptake through roots. Climate change is likely to change the distribution pattern and boundaries of several species, causing altitudinal and latitudinal shift in the vegetation zones.

Vegetation is also expected to shift in response to change in precipitation. Drought-tolerant/drought-enduring species are replaced with wet-tolerant ones and vice versa (Smith et al. 1992). Temperate forest comprises around 20% of the total world's plant biomass and nearly 10% of terrestrial carbon. The net radiative forcing of temperate forest is not yet clearly understood. The annual atmospheric mean temperature is influenced by changing biogeophysical forcing which ranges from low albedo in winters to high evapotranspiration in summer. Either higher albedo followed by deforestation would compensate emission of carbon, causing negligible effect to the temperate forest, or decreasing evapotranspiration because of deforestation would magnify biogeophysical warming.

1.2.1.1.3 Taiga/Boreal Forest

Taiga or boreal forest ecosystems are situated in the earth's Northern Hemisphere. Taiga forest is the largest continuous biome in the world, which spreads across Alaska, inland Canada, Russia, inland Norway, Sweden, Finland, northern Kazakhstan, Japan and Mongolia. Although the biodiversity of boreal forest is low, its forest cover constitutes 29% (1.4 billion hectares) of global forest cover. The carbon reserve in boreal forest is much more compared to carbon reserve of combined tropical and temperate forest. Around 30% of the boreal forest is exploited due to logging and other development projects, and only 12% is safely reserved worldwide. Out of all terrestrial ecosystems, boreal forest is most sensitive to climate change and global warming. The climate change is expected to have acute impact on the boreal forest. In response to climate change, the biodiversity of boreal forest is expected to alter, and the plant growth is predicted to reduce. Different climate models have pointed increased warming in Arctic region compared to global average warming. Over few centuries, the increase in average temperature is twice as rapid in Arctic zone compared to average global temperature (IPCC 2007). While analysing relationship between climate change and boreal forest, it is important to distinguish between old-grown trees and managed trees because managed forest is under big influence of human activity. Boreal forest is supposed to react non-linearly to the changing climatic conditions (IPCC 2007). The emission and sequestration of carbon in boreal forest are controlled by growth of vegetation, extent of forest fires and extent of change in permafrost and decomposition of organic matter. Higher level of CO_2 may directly affect growth of trees by affecting photosynthesis. Disturbances such as forest fires release remarkable carbon into the atmosphere and alter normal carbon budget. These factors are projected to bring modification in boreal forest growth and soil processes. The snow-covered tundra has high albedo. With loss of boreal forest and increased incidence of forest fires, the changing albedo is expected to slow warming. In lower climate of Taiga forest, the low albedo would have warming effect.

1.2.1.2 Grassland Ecosystem

Grassland ecosystems are the ecosystems dominated by graminaceous plant species. It provides shelter to sizable human population and livestock. Except Antarctica, grassland ecosystem occurs in all the continents naturally and covers 24% of the total landmass of the earth. Grassland ecosystem also supports several specifically adapted species of reptiles, plants, mammals and birds endemic to that ecosystem.

The precipitation in grassland is neither surplus enough for the growth and support of forest nor scanty enough for the development of desert ecosystem. Grassland is an area that fall between excessive rain and desert. In grassland ecosystem, mean temperature ranges between 0 and 25 °C, while annual rainfall ranges between 5.9” inches and 47.2” generally. An image of grassland ecosystem is mentioned in Fig. 1.2. Grassland ecosystem is broadly classified into tropical and temperate. Among temperate grasslands, the grasslands that occur in Eurasia are termed steppes, North American grasslands are called prairies and those of Argentina are called pampas. Savannas of northern Australia and sub-Saharan Africa fall under tropical grasslands.

The low height vegetation of grassland ecosystem makes them recipient of abundant sunlight and therefore susceptible to invasion by alien species. Grasslands due to their extensive area and large no of livestock, play an important role in biogeochemical cycles and climate feedback mechanism. While grasslands are responsible for significant carbon storage, they are also responsible for emission of methane (CH_4) and nitrous oxide (Jones 1997). The structure and function of grassland ecosystem are such that it makes it more vulnerable to climate change compared to other terrestrial ecosystems (IPCC 2001). Pollution; conversion of grasslands into agricultural land; use of grasslands for road construction activities and introduction of invasive species are some of the anthropogenic activities that put the grassland ecosystem under great risk. Pollution generally disturbs the fertility of soil and growth rate of plants. Grassland stores ~20% of the soil carbon globally, and changes in grassland carbon stock are likely to have long-term effect on the carbon cycle.

Different climate scenarios predict that climate change can lead to decrease in soil moisture and hence develop water stress in temperate grasses. In tropical grass,

Fig. 1.2 Grassland ecosystem

water stress condition is a highly growth-limiting factor, and under the predicted climate change, it is considered to be likely affected. In case of increased CO_2 level, the stomatal conductance is decreased in most of the species. The reduced stomatal conductance will cause reduced transpiration at leaf scale and efficient utilization of water for consistent plant growth.

1.2.1.3 Mountain Ecosystem

Mountain ecosystem represents the earth's 25% of the land surface. This unique ecosystem covers all the latitudinal stretch and all the climatic zones. It serves as home to 26% of the population worldwide and provides ~100% of the freshwater resource in arid and semi-arid regions having critical availability issue (Diaz et al. 2003). Mountains have been recognized as biodiversity hotspots so as to commit to the sustainability of its environment which encompasses rich flora and fauna. Mountain ecosystems are at potential risk to natural disasters including landslides and tectonic movements and human-induced land degradation, causing ecosystem alteration. These factors make high elevation ecosystem sensitive and vulnerable to global climate change.

The global warming has led to upward shift in the distribution of the plant species occurring in mountain ranges such as Alps in Europe (Vittoz et al. 2009). The upward shift in plant distribution is also observed in the mountain ranges of Iberian and Norwegian Scandes (Engler et al. 2010). The valuable resources from ecosystem services and rich biodiversity will be negatively affected by the climate change. The weather conditions, vegetation and hydrology change rapidly with the elevation; therefore climate change detection and impact assessment are clear and easy in mountain ecosystem. The species distribution model forecasts massive reduction in plant species by the end of the twenty-first century in mountain ecosystem due to climate change scenario (Dirnböck et al. 2011). According to Rathore et al. (2019), a species found in Himalayan ecosystem named *Taxus wallichiana*, popularly known by the name Himalayan yew, has been projected to shrink in its climatic niche by 28% in representative concentration pathways (RCP 4.5). The compound Taxol derived from *T. wallichiana* is known to possess anticancer properties. In Himalayan ecosystem if the present climate change scenario continues to persist without any mitigation measures, then 25 ± 16% of the total mountain species are predicted to lose their habitat by 2070–2100 (Dirnböck et al. 2011). In the face of changing climate, some studies evidenced evolutionary change in some species. Most of the trend analysis suggest mountain ecosystem to be more exposed to climate change compared to low elevation ecosystems.

Chapter 13 of Agenda 31 documented in the United Nations Conference on Environment and Development (UNCED) held at Rio de Janeiro in June 1992 clearly expresses concern regarding deteriorating environmental health of several mountain ecosystems. The mountain ecosystems are deteriorated because of certain factors such as over grazing, deforestation and cultivation of marginal soils that make mountain ecosystems prone to landslide, soil erosion and loss of biodiversity and habitation. These issues need to be addressed and curbed as part of mitigation and management of mountain ecosystem (Fig. 1.3).

Fig. 1.3 Mountain ecosystem

1.2.1.4 Desert Ecosystem

Desert can be defined as any area that are arid and receive annual rainfall less than 25 cm. Desert ecosystem is characterized by intense sunlight, meagre moisture, high evapotranspiration and lashing wind. The days are extremely hot because the arid soil quickly heats up in cloudless sky of desert, while in night the heat is radiated back through the atmosphere, making it colder. Scanty rainfall and high evapotranspiration promote growth of sparse perennial vegetation and scattered shrubs. Scanty rainfall in desert can be attributed to geographical positioning of desert in rain shadow regions and subtropical high in which high pressure restricts cloud formation and rainfall. On the earth's surface, desert ecosystem occurs near 30° northern and southern latitudes. The air current over the globe creates descending dry air belt over 30° northern and southern latitudes. Despite extreme climatic conditions, desert ecosystems are known for brilliant biodiversity. The desert flora and fauna are well adapted anatomically, morphologically, physiologically and behaviourally to withstand harsh conditions. The vegetation adapted for desert habitat include succulents, ephemeral annuls and desert shrubs.

The apparent climate change has already affected some desert of the world by casting drought and decreasing rainfall by 40% since the past five decades. The increasing temperature will turn desert dryer and elevate the water stress which will put many species under huge risk of loss. Since the past five decades, the vegetation has reduced and caused endangered species such as *Sonoran pronghorn* and *Antilocapra americana sonoriensis* (subspecies of antelope) under the threat of extinction because these animals are dependent on the herbaceous plants, cactus and desert shrubs. The loss of vegetation will ultimately lead to loss of animals.

1.2.1.5 Agricultural Ecosystem

Agricultural ecosystem is an artificial ecosystem. It is altered and controlled by humans. It is different from natural ecosystem because it contains few species unlike natural ecosystem which is complex and diverse containing hundreds or thousands of different types of flora and fauna species. Under the threat of climate change, it is challenging to feed increasing global population.

Climate is a determining factor for the growth of agricultural ecosystem. Climate change is supposed to have positive and negative impact on agricultural sector. Climate change can impact agricultural productivity and influence future food security. They may trigger abiotic stress in agricultural crops and may escalate pest/insect and pathogen infestation which can clearly reduce the crop productivity. Water plays a central role in agricultural practice as the world's 70% of the total water withdrawal is for the agricultural practice. Around 80–90% of freshwater is utilized in agricultural sector in developing countries. The water availability is affected by the global warming-driven drought. Moreover, increasing temperature increases rate of transpiration in plants which decreases moisture level in the soil. Agricultural sector is known to be a major driver of climate change. In spite of increase in agricultural land by 10% since the last 40 years, the per capita agricultural land has decreased. It is because of limited available land and growing population. This is evident from the fact that agricultural land in South Asia has remained constant to 223 million hectares since the last two decades. Soil degradation by anthropogenic activities has escalated since 1950s. Every year 12 million hectares of land is deteriorated to desertification. Land degradation, to many extents, can be prevented or reversed by adding nutrients to the soil, buffering soil acidity, rebuilding top soil and re-establishing vegetation.

Likewise, the agricultural productivity has decreased by 13% in Central America and Africa since the last 50 years. Agricultural sector happens to be highly sensitive to the climate change. Therefore, any changes in existing climatic conditions will certainly affect agricultural process and yield. However, sensitivity of agriculture towards climate change is not certain to some extent because of regional variation in climatic conditions such as temperature, rainfall, soils, cropping systems and management practices. The increase in climate change will lead to increase in climate variability and hence losses in crop yield. The response of different crops towards climate change is expected to be complex. It is also challenging to understand and predict the impact of parasites and insects on crop production as several components in crop production system interact concurrently in extremely nonlinear fashion. Crop production generally suffers huge yield loss because of a wide range of insect infestation. These pests are highly influenced by abiotic factors such as temperature, which influence species establishment and abundance in particular region. Most poikilotherms are physiologically adapted to restricted temperature range. Therefore, climate-driven changes in temperature and rainfall pattern, may shift the temperature range of many insects and pests. Sometimes new combinations of insects may arise in response to altered climatic conditions. Similarly, frequent occurrence of extreme events such as storms, heat waves and heavy rainfall may disturb life cycle (growth, development, reproduction) of biological control agents and their pest prey. Therefore, in order to adopt mitigating strategies, modelling tools and approaches must be deployed to forecast distribution of insects at local and global scales in past, present and future climatic scenario. This can be done by understanding insects' requirement of environmental parameters; crop-pest system and the climate data under climate change condition can be obtained from global circulation models.

As agriculture is a key element of global economy, it is challenging to secure sufficient high-quality crop production to meet growing demand while ensuring biodiversity conservation and safeguard and management of natural resources. According to third assessment report of IPCC (2001), vulnerability is function of exposure, sensitivity and adaptive capability. It is, therefore, foremost important to analyse the impact of changing climate on agricultural sector and study its vulnerability for risk analysis. This can help to develop proactive adaptive measures towards climate change, which can ensure sustainable agricultural practice, growth and development.

1.2.2 Wetland Ecosystem

Wetlands, one of the paramount productive habitats on planet earth, are distinguished as a distinct ecosystem where dry land is covered by water bodies. As per Millennium Ecosystem Assessment report, wetlands are known to cover 1.2 million square kilometres globally. According to Ramsar Convention, wetlands include mangroves, flood plains, marshes, coral reefs, forests, rivers, rice fields, peatlands and the edge of a lake or ocean.

The diversity in wetland is governed by climatic, hydrological and geomorphological factors**.** Attributed to the remarkable productivity and diversity, wetlands offer incredible extensive ecosystem goods like food, genetic resources, fossil fuels, water supply and regulation services such as wastewater treatment, nutrient cycling, flood control, erosion control and climate regulation (Llorens 2008). However, since the twentieth century, wetlands are declining by about 64–71%. According to Agardy and Alder (2005), around 20% of coastal wetland is lost every year. Though certain non-climatic drivers, viz. wetlands drainage, deforestation, habitat fragmentation, sewage, eutrophication, pollution, introduction of invasive species, etc., contributed a major portion to wetland losses, still the effects/impacts created by climate change cannot be overlooked (Scavia et al. 2002). More specifically, pressure on tropical wetlands as a result of climate change are expected to be intervened through effects of changes in temperatures/humidity, hydrology (principally those leading to flood or drought conditions) and land use pattern (Ferrati et al. 2005). The coastal wetlands such as mangroves are also altered by the rise in sea level (Mitsch et al. 2010). The climatic impacts range from changes in availability of water in rivers to marine disturbance and changes in biodiversity (Roessig et al. 2004; Chiabai et al. 2018). The detailed devastating effects of climate change on the abiotic and biotic (starting from individual organisms to populations and then to communities) components on different types of wetlands are discussed in the following section.

1.2.2.1 Peatlands

Peatlands which cover 3% of the land's surface globally are characterized as the areas that have a naturally accumulated peat layer on the land surface (Page and Baird 2016). Peatland ecosystems are known to deliver a number of benefits, for instance, biodiversity protection, natural risk mitigation, storage of carbon and its sequestration and recreation opportunities. Peatlands primarily exist in boreal regions owing to the cold waterlogged conditions which promote accumulation of soil organic carbon (Matthews and Fung 1987; Bridgham et al. 2000). Since peatlands cover large area, the impact of climate change on it is also large.

According to Briggs et al. (2007), changes in hydrological cycle affect the dynamics of peatlands. An increase in temperature could cause a change in hydrology and increase the chances of wildfires (Hengeveld 2000). Peat fires are further a source of greenhouse gas emissions (carbon dioxide and methane) into the atmosphere. In Europe, it is estimated that around 360 Mt of CO_2 year^{-1} is produced from peatlands that are drained for forestry and agriculture. On the other hand South Asia emits approximately 700 Mt of CO_2 year^{-1} from peatlands in spite of having smaller area compared to Europe (Joosten 2009; Hooijer et al. 2010). The drainage of peatlands in addition to greenhouse gas emissions also increases the peat carbon into the streams and drains in dissolved and particulate form. This leads to lowering of height of peatland surface (subsidence). In California, drainage of peat has been followed by subsidence of land between 1 and 8 m on the Sacramento–San Joaquin River Delta. This is followed by levee failure, flooding and saltwater intrusion which ultimately result in an increased amount of nonfarmable land (Drexler et al. 2009). Organic material decomposition, increased peat formation (in the Arctic region), permafrost degradation and changes in plant communities are some of the other effects of climate change which require more consideration.

It is well known that peatland is an important carbon pool containing carbon in the range of 329–525 × 10^{15} g (Bridgham et al. 2006). However, over the millennium, climate models predict that with the climate change, their input-output models had been significantly altered. Bridgham and his coworkers (2008) examined responses of bogs and fens with respect to warming and changes in water tables. While bog mesocosms are known to accumulate more soil carbon in wetter mesocosms, no further water table effects were reported after 3 years. Conversely, fen mesocosms, in response to drier and warmer mesocosms, either exhibited loss or showed no change in soil carbon.

In plants, major transition in vegetation was observed which was likely due to the increase in wetness of climate. Belyea and Malmer (2004) reported the dominance of *Sphagnum* species at progressively lower heights above the water table followed by *S. fuscum*, *S. rubellum* and *S. magellanicum* which occupy the highest and driest niches, intermediate niches and lowest and wettest niches, respectively, in response to increasing transmissivity/water input in Store Mosse in southern Sweden. In the North American *Sphagnum* peatlands, Wieder (2000) reported decay in the net primary production in the upper 30 cm of peat with no change in net carbon accumulation in response to increase in temperature and/or increase in precipitation.

1.2.3 Coral Reefs

Coral reefs are underwater marine ecosystems with greater diversity. Although, these ecosystems cover merely 0.2% of the world's oceans, about 25% of marine species exist in coral reefs indicating the highest level of biodiversity (Cesar et al. 2003). Coral reefs bring in massive capitals to coastal countries through fishing and tourism. Additionally, they protect the shores and islands from storms. However, coral reefs all around the world are suffering from the problems of immense die-outs. Overfishing and pollution are considered to be the foremost intimidations to the integrity of reef ecosystems, but the increase in sea surface temperature linked with climate change makes the coral reefs vulnerable to damage (Hughes et al. 2003). In recent times, a rise in sea temperature has caused extensive coral bleaching worldwide. Figure 1.4 depicts the coral reef bleaching.

Moreover, elevated greenhouse gas emissions (carbon dioxide) are inducing ocean acidification that may further lead to loss of coral reefs. Table 1.1 summarizes the comparison of effect of climate change on the different regions around the world during 2004 and 2007. The huge degradation of coral reef is the result of mass coral bleaching and decreasing calcification rates.

Coral bleaching is the result of symbiotic algae, i.e. zooxanthellae, expulsion under stress conditions such as increase in ambient temperature of approximately 1 °C. These microscopic dinoflagellate algae live inside the coral tissue and carry out photosynthesis. By doing so, the algae provides corals up to 90% of energy for their growth and reproduction (Hoegh-Guldberg 1999). The sustenance of such increased temperature for several weeks leads to whitening of the corals. Prior to the 1980s, there is hardly any report of mass coral bleaching, but during 1998, high sea surface temperatures and El Niño effect at the same time caused events of global coral bleaching and mortality. As per reports, the devastating events of mass bleaching have been observed in the Northwestern Hawaiian Islands of the United States of

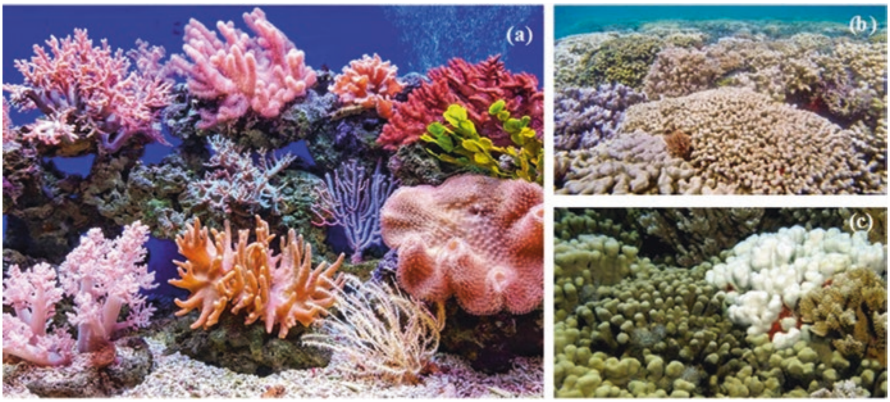

Fig. 1.4 (**a**) Coral reef, (**b**) before bleaching and (**c**) after bleaching (Source: https://phys.org/news/2019-04-soft-tissue-coral-tougher-climate.html)

Table 1.1 Status of coral reef cover around the world

S. no.	Region	Coral cover	
		2004	2007
1.	Daya Bay, Guangdong	30%	33%
2.	Japan	30.4%	27.1%
3.	Wakatobi National Park, south of Sulawesi, Indonesia	45%	22.0%
4.	Bar Reef, Sri Lanka	40%	70%
5.	Fiji	38%	40%
6.	Cozumel, Mexico	28%	18%
7.	Chinchorro, Mexico	27%	12%
8.	Caye Caulker, Belize	48%	18%
9.	Gladden Spit, Belize	15%	8%
10.	Cayos Cochinos, Honduras	26%	15%

America in 2014. Similar mass bleaching effects were also observed in Great Barrier Reef of Australia during the year 2016 and 2017. It is clear that the coral is instrumental in providing large range of microhabitats that support vast biodiversity. Mass bleaching events and associated mortality can thus amend the structure and function of the whole ecosystem. The coral loss can dramatically reduce the abundance and diversity of coral reef fish which in turn disturbs the organismal relationships thereby affecting the ecological processes (Burns et al. 2016; Darling et al. 2017). One such evidence is reported in a case study, where coral reefs of Seychelles demonstrated a tremendous decrease in fish abundance, particularly of *Chaetodontids* and *Plectroglyphidodon johnstonianus* fish species due to mass coral bleaching. As an after-effect of 1997–1998 El Niño event, an increase in invertebrate feeding fish species was reported by Spalding and Jarvis (2002). However, no effect was observed on the number of other terrestrial herbivores like *Plectroglyphidodon lacrymatus*. Lindahl et al. (2001) reported reduction in the number of damselfishes on the Tanzanian coral reefs. The most widespread study on the long-term effects of the 1997–1998 mass coral bleaching on reef fish assemblages has been done by Garpe and his colleagues (2006) in Tutia Reef situated in Mafia Island Marine Park, Tanzania. The 1997–1998 mass coral bleaching also resulted in habitat alteration and fish assemblages with low taxonomic richness. Hence, it becomes difficult for fish assemblages to recover during such catastrophic climatic events, if continued in the future.

1.2.4 Aquatic Ecosystem

Aquatic ecosystems which comprise freshwater and marine ecosystems are important components of the global environment (Fig. 1.5). In addition to being the repositories of biodiversity, they also provide significant ecosystem services including fish production, recreational opportunities, water for drinking and irrigation purpose and climate regulation (Gunkel et al. 2015; Boulton et al. 2016; Grizzetti et al. 2016). Over the last few decades, aquatic systems are under continuous stress. The changes

Fig. 1.5 Aquatic ecosystem

in temperature and precipitation across the globe pose a serious threat to the aquatic ecosystems (both freshwater and coastal). Since, the biological processes depend on temperature, a change in temperature regime can abruptly influence the aquatic organisms' growth rate and behavioural performance. It might also affect the habitat preference of species and their survival. Specifically, species with narrow niche generally suffer from increased risk of extinction. Amphibians are best example as they are experiencing a dramatic decline in many parts of the globe. According to Sutton et al. (2015), Cayuela et al. (2018) and Ashrafzadeh et al. (2018), salamanders due to their limited dispersal abilities and migration have been recorded as vulnerable species to the effects of climate change. Amphibians migrate for breeding and hibernation during spring and autumn. Sutton et al. (2015) documented that loss of amphibians occurs due to synergistic action of climate change, habitat loss and fragmentation. Due to continuous effects of climate change, the endemic salamanders of Iran might shift to higher elevation by 2050 and 2070. Moreover, sea level rise as a result of global warming can heighten the coastal erosion, increase the coastal flooding and subsequently decrease the accessibility of freshwater to humans and ecosystems in coastal zones (Llorens 2008). More specific and exhaustive evidence of growing impacts of climate change in lakes and marine ecosystems is addressed in the following sections.

1.2.4.1 Lakes

Lakes are water bodies that are bordered by land. Lakes on the earth's surface are not evenly distributed; most are located in the Northern Hemisphere. Canada has nearly 60% of the world's lakes (Meybeck 1995). Based on the vertical temperature profiles and seasonal variation, lakes are divided into different strata. During summer, the upper part of lake, the epilimnion, becomes warmed by the sun with small temperature gradient. The second layer, metalimnion (or thermocline), is characterized by a rapid decline in temperature. This layer separates the epilimnion from the bottom layer, i.e. hypolimnion, the cooler part of lake. The global climatic variability severely disturbs the lakes' heating, cooling, mixing and circulation patterns (Sahoo et al. 2016). The instantaneous physical impacts of climate change on lake ecosystems comprise warmer temperatures, alterations in the thermal stratification and complete drainage of the waterbodies (Saros et al. 2012).

The warming of lakes as a result of rising earth's temperature could initiate an increase in water evaporation rates. If climate change is not controlled, then by the end of the century, global lake evaporation will accelerate by 16% as a consequence. Egyptian lakes, e.g. Lake Manzala and Lake Qarun, suffered from the incidence of gradual evaporation. In Australia, every year as much as 40% of water storage capacity of lakes is lost to evaporation as a result of climate change (Helfer et al. 2012). Due to such pronounced increase in evaporation rates, fall in the lake levels is likely to observe. Lake Superior has lost 2 feet of water every year through evaporation. The lakes found in mid to high latitudes where water is usually in frozen state, also show late freezing in winter and earlier thawing in the spring as a result of evaporation. Due to this, ice period gets shortened, thereby causing a higher absorption rate of solar heat.

The surface area and depth of lakes, wind exposure, altitude, latitude and elevation of lakes are some of the factors which must be taken into consideration while evaluating the climate change impacts on lakes. These factors govern the incidence and extent of thermal stratification which thereby control the periodic range of water habitats accessible to species (Llorens 2008). Over the past 33 years, warming of Lake Tahoe was reported with increasing water temperature as a result of climate change (Coats et al. 2006). Warming air temperatures increases the epilimnetic water temperatures and strength and period of stratification and also altered the depth of thermocline (Schindler et al. 1990; Dobiesz and Lester 2009; Rempfer et al. 2010; Ficker et al. 2017). Advancement of stratified period by 20 days or lengthening of stratified period by 2–3 weeks in several lakes in Europe and North America is one of the strongest evidences of increased thermal stability due to climate change. Additionally, run-off patterns of lakes are also changed which thereby affects the lake levels. Such physical changes in lakes, in turn, affect the aquatic biotic communities in multiple ways. The effect on ecosystem and biotic community is complex and may occur through introduction of invasive species and shifts in algal communities (Rühland et al. 2008; Edlund et al. 2017).

A number of studies have surveyed change in flora and fauna biodiversity in relation to climate change. It has been reported that the growth and metabolic rates of fish and aquatic invertebrates are strongly influenced by the change in environmental temperature (Ficke et al. 2007; Rypel 2009). Aquatic organisms such as fish usually thrive at a particular temperature range. Warm-water fishes usually breed at higher temperature contrary to cold-water fishes that can breed at very low temperatures. Chinook Salmon eggs hatch well at 16 °C, whereas the eggs of Trout cannot hatch over 14.4 °C (Jain et al. 2013). With the increase in temperature, profound effects are found upon the character and life of a cold-water fishes. If the lake temperature is increased by 5–10 °C, there is a probability of replacement of cold-water fish with that of warm-water fish.

Moreover, fluctuations in the distributions and assemblage of macroinvertebrates have been seen when lakes along geographical gradients were surveyed. It is reported that not only high-latitude region but both Eurasia and North America also exhibited such variability in distribution of midges (small flying insects) (Nyman et al. 2005; Barley et al. 2006). Patalas (1990) found that in areas with mean temperatures of 15 °C, maximum species richness of zooplanktons was seen, which was found to decline with both rise and drops in temperature between 45 and 55° N. Benke (1993) documented that for every 1 °C increase in temperature, a 3–30% increase in production of macroinvertebrate was seen. The lake warming could also result in an increase in nuisance algae and decline in the habitat of fish. The severity of such impacts is seen in the shallow lakes. In shallower lakes, bulk lake volume is expected to be warm; henceforth fish fauna (especially large, predatory fish) which needs cool hypolimnetic water is likely to suffer from habitat degradation. The decline of native fish species moreover facilitates supremacy of non-native species. One such case is evidenced in Lake Tahoe (Vander Zanden et al. 2003). In Lake Tahoe, climate warming and local land use practices are considered to be the major reasons behind invasion of non-native aquatic species. Elevated water temperatures promote growth of aquatic weeds comprising non-native *Myriophyllum spicatum* (Eurasian watermilfoil) and *Potamogeton crispus* (curly leaf pondweed). Over time, presence of such aquatic weeds favours the proliferation of warm-water fish species. Some of the non-native warm-water fishes found in Lake Tahoe are *Micropterus salmoides*, *Lepomis macrochirus*, *Ameiurus nebulosus*, *Carassius auratus*, *Oncorhynchus mykiss*, *Pomoxis nigromaculatus* and *Salmo trutta* (Kamerath et al. 2008). Subsequently, introduction of such species in addition to increased stress on populations of native fish species could also reduce food web efficiency and sport fishery production. Some invasive species such as zebra mussels and lampreys extend their ranges into new territories and cause damage to harbours and waterways, e.g. The Great Lakes.

Warming of lakes increases the primary productivity of the lakes. Likewise, the rate of photosynthesis is found to be higher with the corresponding increase in the amount of dissolved CO_2 (and for some species HCO_{3-}) (Llorens 2008). In the end of the nineteenth century, a striking shift in phytoplankton assemblages such as diatom was seen in retort to the warming of the Arctic (Overpeck et al. 1997; Sorvari and Korhola 1998). In many dimictic lakes, silicified diatoms are considered to be a vital constituent of seasonal phytoplankton maxima which further control the populations of zooplanktons (Winder and Schindler 2004a). The algal dynamics and community structure are controlled by length of the open water season and the timing, period and strength of thermal stratification. For example, earlier development of diatom blooms in lakes of North America and Europe has been observed in response to earlier onset of thermal stratification which is due to warmer temperatures (Winder and Schindler 2004b; Adrian et al. 2006). Weckstrom and Korhola (2001) reported temperature-induced response of distribution of diatoms across lakes in Arctic Lapland. The highest species diversity of diatoms exists in the lakes located in the mountain birch woodland in the forest-tundra transition zone. On the other hand, in some lakes of Europe and North America, a systematic replacement of diatom *Aulacoseira* spp. (heavily silicified diatoms) by *Cyclotella* spp. (small centric species) has been seen which is because of changes in mixing regimes of lakes and the increase in stability of thermal stratification.

Climate change also fortify the negative consequences of eutrophication. By the term eutrophication, we mean a process of excessive plant and algal growth as a result of increase in minerals and nutrients. Eutrophication will likely to cause many problems, for instance, reduction in dissolved oxygen content in water, water clarity reduction and impairment of water quality. In the worst scenarios, there occur massive blue-green algal blooms and intense changes in fish stocks. One of the most interesting cases of climatic eutrophication is reported in Lake Tahoe. During summer stratification, the vertical partitioning of the water column is known to abolish the mixing of nutrient-enriched hypolimnion with the nutrient-poor epilimnion (Paerl et al. 1975). The reduced deep mixing to Lake Bottom thus causes a substantial consequence on nutrient supply to the epilimnion. In addition, dissolved oxygen concentration in the hypolimnetic water approaches to zero which increase likelihood of anoxic conditions in the hypolimnion. This significantly hampers habitats of resident lake's salmonid community and cold-water fishery (Sahoo et al. 2016).

1.2.4.2 Marine Ecosystems

Marine ecosystems is one of the largest among all ecosystems and occupies around 71% of surface of the earth (Fig. 1.6). The presence of dissolved salts (particularly sodium and chlorine) makes this ecosystem distinguishable from freshwater ecosystems. Over the past decades, there has been substantial change in the marine biodiversity, including mass destructions of several marine mammals (Raup and Sepkoski 1982). Most of these incidents are predicted to link with the climate change that disturbed the temperature of oceans and impaired its productivity (Vermeij 2004). The other noticeable changes in the marine ecosystems due to climate change includes thermal stratification, rise in sea level with the consequent coastal erosions, ocean currents, loss of permanent ice cover and threats to polar creatures and their indigenous way of living (Schär et al. 2004; Schmittner and Galbraith 2008).

Sea level is expected to rise as much as 69 cm during the next 100 years as a consequence of thermal expansion of ocean water and faster melting of ice sheets and glacier. The sea level rise will cause serious impacts on marine ecosystems. According to McFadden et al. (2007), marshes were estimated to suffer global losses of 33% and 44% due to rise in sea levels of 36 and 72 cm, respectively, between the years 2000 and 2080. Other associated impacts of global sea level rise

Fig. 1.6 Marine ecosystem. (**Photo credit:** James Thornton, Johnny Chen and Milos Prelevic)

include vegetation losses, coastal erosion, increased salinity in estuaries, increased flooding in low-lying areas and damage to intertidal zones with significant change in sediment and transport of nutrients (Llorens 2008). A large amount of aquatic biodiversity such as migratory fishes, coral reefs, turtles, aquatic crustaceans and aquatic birds, viz. flamingo, pelicans and aquatic warbler, are vulnerable to such drastic effects of sea level rise (Newson et al. 2009).

On the local level, ocean warming is expected to cause slow changes in species structure that in turn will lead to an increase in diversity of marine species. The first reports in this context were given by Southward et al. (1995) during their studies on the English Channel. Due to climate warming, warm-adapted species of intertidal and pelagic communities showed an increase in abundance with corresponding decrease in cold-adapted species, resulting in net increase in species diversity.

On the regional scale, shift of the geographical ranges of species is observed due to climate warming. In the North East Atlantic, a number of rocky intertidal species have extended their range as a result of climate change. Likewise, southern species such as *Osilinus lineatus* da Costa and *Gibbula umbilicalis* da Costa have extended their range towards north and north-eastern region (Mieszkowska et al. 2006). A number of southern warm-tolerant species in the United Kingdom have extended their range northwards and eastwards along the Welsh and Scottish coastlines and eastwards into the cooler Eastern English Channel basin.

Substantial indirect effects of climate change on fish community recruitment and migration pattern of fish species have been witnessed in marine ecosystems. It has been found that climate change has decreased the likelihood of recruitment in fish populations (Cushing 1995). In the north-east Atlantic, Brunel and Boucher (2007) summarized that 40 fish stocks of 9 species were likely to exhibit decline in recruitment with warming of sea. According to Planque and Frédou (1999), the interannual variations in temperature affect the recruitment of Atlantic cod (*Gadus morhua*) stocks in such a way that negative relationship is observed for fish stocks located in warm water, whereas the relationship is positive for fish stocks located in cold water. In the Bering Sea, walleye pollock (*Theragra chalcogramma*) in its juvenile form is an imperative forage fish for adult pollock, other fishes, marine animals and birds. The instabilities in recruitment, therefore, affected the entire food web of Bering Sea. The migration patterns showed alteration with the change in climate. Such impacts were reported around 3.8 million years ago during the trans-Arctic interchange. Examining the variation in the migration of large pelagic fish, northern Bluefin tuna, *Thunnus thynnus*, Polovina (1996) reported climate-induced change in prey abundance to be responsible for such alteration. During the past decades, a decline in the migration of bluefin to the eastern Pacific was observed. According to bluefin stock assessment studies, this decline corresponds to the decrease in migration of bluefin out of the western Pacific. More specifically, the trans-Pacific migration dynamics of bluefin is linked with population dynamics of Japanese sardine, *Sardinops melanosticta* (a prey of bluefin) in the western Pacific. Opposite to the scarcity of *Sardinops melanosticta*, its abundance off Japan leads to decline in the bluefin migration to the eastern Pacific. Such abundance in sardines off Japan is more likely due to the climate forcing (Soutar and Isaacs 1974).

In the Baltic Sea catchment area, rise in average temperatures and increase in rainfall have been encountered as consequences of climate change. The increase in winter rains together with the lack of ground frost promoted increases nutrient flows into the Baltic Sea from the catchment area, carrying with it increasing amounts of the key nutrients (phosphorus and nitrogen). The pacific marine ecosystem of Canada is also affected by climatic change and associated problems of sea water temperature increase, acidification, sea level rise and altered oxygen content. Species like Pacific salmon, rockfish, invertebrates and elasmobranchs are becoming more vulnerable due to warming trends of sea water in southern parts of British Columbia. The livelihood of the people of British Columbia and their food security have been impacted much by climate change due to shifts in fish supply and distribution (Álvarez et al. 2019). Zhang et al. (2019) reported that a Japanese marine fish *Sillago japonica* will shift its habitat northwards. On further exposure to climate change, it will lose its potential habitats by the year 2090–2100. The Gulf of Riga, Gulf of Finland and the Archipelago Sea were likely to receive increased riverine nutrient loads, thereby resulting in higher algal biomass (Andren et al. 2000; Karlson 2002). Further, the upwelling in nitrogen and nitrogenous compounds into aquatic water bodies expedites the spread and establishment of many foreign species and creates new opportunities for them to become invasive. Found in marine environments, invasive species include weeds, bacteria, fungi, insects, fish, snails, mammals and other species. Certain group of researchers reported the entry of invasive species like *Caulerpa taxifolia* (Vahl) C. Agardh and *Caulerpa racemosa* var. *cylindracea* into the Mediterranean Sea (Meinesz 2001; Verlaque et al. 2004). Earlier in 1876, an invasive species of *Brachidontes pharaonis* (a small Erythrean mytilid mussel) is known to invade the northern access of the Suez Canal (Galil 2007). With time, it negatively impacted native biodiversity and ecosystem services as well and caused harm to the livelihood and health of island inhabitants. In addition, they might cause changes in the chemistry of water and alter the biogeochemical processes and food webs (Dukes and Mooney 2004).

Flora constitute an important role in the marine ecosystem. Algae is a photosynthetic organism that becomes an indispensable part of marine flora. In the polar marine environments, the presence of sea ice governs the algae production. Algae serve many functions including regulating carbon cycle, providing food and energy and acting as indicator of water quality. Besides these benefits, algae also function as a base of most of the Arctic food web and also maintain several important species such as Arctic cod. In turn, Arctic cod further directly or indirectly supports numerous marine species including narwhals, polar bears, seals etc. It has been observed that with the melting of polar ice, reduction in algae takes place which thereby diminishes the Arctic cod resulting in disturbance of the food web. Bladderwrack (*Fucus vesiculosus*) is another important seaweed that is found in the North and Baltic Seas (Doney et al. 2011). Bladderwrack serves many functions: important oxygen provider and food source for numerous organisms. It generally colonize the intertidal regions. Over the past four decades, its population has decreased by more than 90% in the western Baltic Sea due to sea water warming. Warming of sea water increases the bacterial growth on the surface of bladderwrack. Intense darkness and high temperature favour the bacterial attack on the algae. Further, abrupt differences in temperature at changing water depths weaken the ability of bladderwrack to defend against aggressors.

Climate change also has drastic implications for aquatic animal populations. One such significant consequence of global warming is the alteration in sex ratio among sea animals. It has been observed that the sex ratios of certain sea animals is determined by temperature. For instance, in sea turtles, due to absence of X or Y chromosome, their sex is determined by the incubation environment during middle third of embryonic development. In the United States, the pivotal temperature of 29 °C produces a ratio of 1:1 of male to female hatchlings of loggerhead sea turtle (Mrosovsky 1988). Above this pivotal temperature, females are produced, whereas temperatures below pivotal lead to production of more males (Yntema and Mrosovsky 1982). According to Howard et al. (2014), within a temperature tolerance range of 25–35 °C, warmer temperature produced females, and cooler conditions produced males. Climate change driving up the temperatures within the nest could lead to a massive feminizing bias in populations of sea turtles. The data from Raine Island, Australia, revealed that an increase in temperatures of 2 °C from the current levels could increase sand temperatures to the levels at which feminization of population may take place. Apart from the effects that increased temperatures could have on sea turtles' sex ratios, rise in temperature can exert a significant impact on growth, abundance and distribution of other aquatic biological communities, e.g. fish. In the fish populations, increase in temperature is foreseen to cause shift in size distribution towards small individuals. It was observed in the North Sea that over a 38-year period, an increase in temperature between 1 and 2 °C could result a decrease in maximum length of haddock, herring, whiting and Norway pout by as much as 29% (https://www.theguardian.com). Increase in temperature increases the need for dissolved oxygen for the fish to survive. Complications occur when temperature rises to the level that causes decrease in dissolved oxygen levels. Low levels of dissolved oxygen mean aerobic scope of fishes get reduced which in turn limit the energy available for activity, growth and other vital rates (Portner and Knust 2007).

1.3 Popular Climate Models and Their Projections

Climatic models happen to be quantitative systems consisting of differential equations to replicate natural climatic interactions of major drivers of climate which include terrestrial system, atmosphere, ocean and permafrost. Climate models are used to understand climate system dynamics and future projections of climate trend. Imbalance in atmospheric temperature is monitored by measuring incoming short wavelength electromagnetic rays consisting of mainly visible and near-infrared radiation and outgoing far-infrared radiation. Many climatic models have been developed and customized in line with latest understanding of carbon dynamics and its interactions with geological, hydrological and atmospheric systems.

Global climate change may have great implications on wildlife and ecosystem health. It can impact parasitic and pathogenic diseases in wildlife and its spatio-temporal transmission pattern. It is very important to predict the probable impact of climate change on wildlife parasites as part of wildlife conservation and disease control strategy. Also, parasites are essential element of the ecological community because they affect the survival of the host, its reproduction and behaviour. Empirical models suggest that changing climate along with anthropogenic interventions can affect phenology of parasite, host population and dynamics of host and parasite. Desert animals worldwide are under potential threat due to global warming and climate change because they have limited source of drinking water. Climate change simulations in Saudi Arabia predict that by the end of the twenty-first century, the ambient temperature will rise to 3–5 °C, while the rainfall trend will remain the same (Al Zawad and Aksakal 2010). Moreover, most of the animals of this region are non-migratory; therefore they will have to cope up with the ambient temperature by maintaining their body temperature below upper lethal level for their survival. A climate model developed by Wilms et al. (2010) predicted the effect of climate change on the population of lizard species named *Uromastyx*. General ecology and thermoregulations of these species are likely to be impacted by the rising temperature. The model predicted decrease in environmental suitability of these lizards by 70–80%, affecting their growth and reproduction as they will be forced to stay below ground for prolonged durations. The *Uromastyx* species is suspected to go extinct from several areas of the Arabian Peninsula.

One of the regional climate models indicates that under the climatic change scenario, the change in temperature of water in Atlantic Ocean and Gulf of Mexico will affect the survival and development of the eggs and larvae of billfish and tuna species. This will bring change in species distribution and affect physiology of the species at different stages of their life span. It is predicted by the model that by the year 2050, due to increasing temperature, nearly 39–69% of habitat of bluefin tuna larvae living in northern Gulf of Mexico will be lost (Dell'Apa et al. 2018). The climate-driven increasing temperature of water in the Gulf of Mexico and nearby areas (Gulf of St. Lawrence and northwestern Atlantic) will drive change in distribution and feeding migration of bluefin tuna (Lamadrid-Rose and Boehlert 1988; Rooker et al. 2012). This may influence fecundity during spawning. Moreover, changes in rainfall pattern will decrease the salinity and increase the temperature of water masses arising from freshwater runoff in Gulf of Mexico, resulting in decrease in population of billfish. Similarly, climate-driven hypoxia condition in the water will escalate metabolic stress in billfish, resulting in decreased reproduction and survival rate. Also, horizontal and vertical expansion of hypoxic water along the water column will lead to habitat compression for billfish and blue marlin (Prince and Goodyear 2006).

Plants and trees, in response to climate change, are showing advanced trend in flowering time causing a change in breaking dormancy process. The dynamic model which is deployed in horticulture assumes that some of the intermediate products produced requires low temperatures and when it is exposed to high temperature are destroyed by heated condition (Erez et al. 1990). The chilling hour model indicated 2.5 times loss in flowering due to greenhouse gas emissions and climate change compared to 1950 baseline data. Chilling hour model, Lantin model and Utah model estimated chilling changes in winter driven by climate change from the year 1950 to 2002 in many regions of United Kingdom. Chill losses were predicted by Else and Atkinson (2010) to disrupt the ability of trees bearing fruits to break dormancy suitably. Thus, the horticulture models are very helpful in guiding to manage orchard and cultivar section.

1.4 Conclusions

Climate change has brought in numerous changes in the physiology, phenology and life cycle of organisms resulting in loss of productivity and loss in migration of species. The effects are invisible in initial stages and cannot be ignored. Adopting sustainable practices to minimize the greenhouse gas emissions is the key mantra to reduce global warming and climate change. If the increasing greenhouse emissions are not checked, it might lead to disastrous effects on the biosphere of the earth. It is important to understand plausible impacts of climate change on resources, organisms and habitat quantitatively in the first place through different climatic models, in order to understand the associated risk and vulnerability. This can help to develop proactive adaptation measures towards changing climate and to ensure sustainability.

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2 A Comprehensive Evaluation of Heavy Metal Contamination in Foodstuff and Associated Human Health Risk: A Global Perspective

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Abstract

Heavy metal contamination has an adverse effect on the aquatic, terrestrial, and atmospheric environment. These may be natural or anthropogenic in origin and not easily degradable. Anthropogenic activities have unwantedly transferred these heavy metals in our food chain and food web. Directly or indirectly these heavy metals have entered in our food through irrigation by wastewater effluent released by industries; scarcity of available freshwater for irrigation, usage of fertilizers and insecticide, and other anthropogenic activities have caused acute and chronic diseases. The dose–response relationship suggests that the heavy metals have a narrow level of lethal concentrations which pose a threat to the target population. Anthropogenic sources of heavy metals generally dominate natural sources, and foreseeing the synergy of this with the degrading environmental conditions, the health of people is a matter of concern. When these heavy metals get accumulated in the human food, it results in abnormalities affecting human survival and mortality. Recent data suggest that the human body gets affected by heavy metal contamination at lower levels than previously anticipated and evidenced. Agrochemicals are resistant and adaptive in nature, and with the increasing dose and newly synthesized compounds to protect crops, undesired side effects and the costs of food production are on a hike. Practices like street food vending and addition of preservatives in packed food increase the chances of heavy metal contamination in food materials. A comprehensive evaluation of the food chain right from the primary producers to consumer level is necessary to ensure food security and quality.

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Anthropogenic activities · Wastewater · Agrochemicals

2.1 Introduction

The heavy metal pollution is one of the world's top environment-related problem, and has risen due with the increasing industrialization and urbanization. It has become one of a very serious threats due to it's deleterious effects on human being and environment (Yang and Sun 2009). With increased economic growth globally in recent years, production and uses of heavy metal has accelerated many folds, leading to pollution of the environment (Raju et al. 2013; Zojaji et al. 2014). Heavy metals have a higher density, atomic weights, or atomic numbers. Due to it's adverse effects exposure of heavy metals are always concidered as a potential risk to human beings and the environment. Toxic metals such as cadmium, mercury, lead, and arsenic are the main causes of human health problems. Contamination of heavy metals can't be physically identified or distinguished because of its colourless, odourless nature and easily get absobed. When environmental conditions changes or exceed the tolerance of the environment, heavy metals get converted in to ionic forms, which are active and bioavailable which may act as chemical time bombs and casues serious threat to the ecological system (Wood 1974). Exposure of even lower concentrations of some of these elements are very toxic to the human body and can cause acute or chronic diseases. In the past, only a few cases were reported about soil contamination by some of the specific heavy metals, but in the recent years, presence of various heavy metals have been reported in the each component of the ecosphere (Zhou 1995). Heavy metals may get released in the atmosphere through gases, dust, smoke from various industries, energy production, metallurgy, transportation, and constructional materials. Only mercury in the atmosphere is present in the form of aerosols and gets deposited in the soil by precipitation and natural sedimentation. Heterogeneous contamination of various heavy metals can intensify the lethal contamination concentration. Pollution by heavy metals in the environment has become a significant ecological concern because it takes a longer time period for degradation and has a longer biological half-life (Abii and Okorie 2011). Anthropogenic source of heavy metals includes various activities like pesticide and fertilizer application in the crop field, untreated effluent discharge from industrial activities, mining activities, and sewage irrigation etc. (Zhang et al. 2011). A report from Central Sweden by Lin (1998) stated that environmental pollution by lead is mainly due to urban industries. The lead contamination can spread or get transported by water and winds from the waste heap/dumps to another surrounding area. Lead contamination of ground water also occurs through percolation/leaching of industrial waste.

Another potential source of heavy metal pollution in the agricultural land is wastewater irrigation from sewage and industrial effluents. Due to lack of fresh water resrouces, domestic wastewater or industrial effluents are used for irrigation in urban and peri-urban agricultural practice (Singh et al. 2010). In India, approximately 73,000 ha of agricultural land is irrigated with wastewater (Kaur et al. 2014). Wastewater irrigation when continuously practised may lead to accumulation of toxicants (including heavy metals) in the soil as well as in vegetable crops (Marshall et al. 2007). Contamination of heavy metals in vegetables generally arises from irrigation of polluted water. However, contamination may also occure due to use of chemical fertilizers and pesticides, during the process of harvesting, transportation of vegetables, and the storage. The pollution of the environment is due to human activities owing to the discharge of heavy metals from tanning industries, lubricants used for maintenance of machinery, etc. Contamination of heavy metals in food via consumption can become a risk to human health. According to a report by WHO and FAO (2007), higher concentrations of heavy metals in India were found in milk and drinking water and have exceeded the safe limit. In peri-urban areas, heavy metal contamination is occurs mainly through dust and aerosols ladden with metals which enters in to the soil, and also gets deposited or absorbed by the leaves of the vegetables and plants (Abii 2012; Kachenko and Singh 2006). Vegetable crops grown in surrounding areas of industrial locations have been reported to possess high elevated concentration of heavy metals (Singh and Kumar 2006). The heavy metals get accumulated in the aquactic ecosystem as well which further get transferred in the fishes and other aquatic organisms. When the contaminated water is used for irrigation, the soil get contaminated and from the soil heavy metals get absorbed by the roots of the plants or crops and get accumulated in different part of the plants. Through the plants, these toxic metals finally entering into the food chain. The heavy metals contaminated fruits and vegetables when consumed through ingestion, causes various types of diseases and abnormalities in human beings depending upon the degree of contamination. Some of the heavy metals are essential in lower concentration to support vital functions but may inhibit enzymatic activities and poses toxic effects on higher concentrations (Koropatnick and Leibbrandt 1995). In past few decades, human health issues are of major concern with reference to the intake common food stuffs including fruits and vegetables contaminated with heavy metals (Milacic and Kralj 2003).

Based on the toxicity, some of the heavy metals such as arsenic, lead, mercury, and cadmium ranked first, second, third, and fourth in the list, respectively. Arsenic, lead, and mercury are ranked as the top three most hazardous substances in the priority list of the Agency for Toxic Substances and Disease Registry (ATSDR). Fig. 2.1 presents an sckechematic representation of sources of heavy metal contamination in the environment.

Cadmium, lead, arsenic, and mercury pose serious health risk when consumed through contaminated food. Cadmium and lead have significant health hazard since these elements are easily accessible to the food chain. Children are more vulnerable when exposed to these elements because it gets easily accumulated in tissues and causes retardation in children and adverse effect on the kidneys, cardiovascular system and auditory system (Rahimi 2013).

This chapter a detailed overeview of heavy metal contamination in foodstuff and associated human health risk. Contamination of foodstuff by heavy metal has

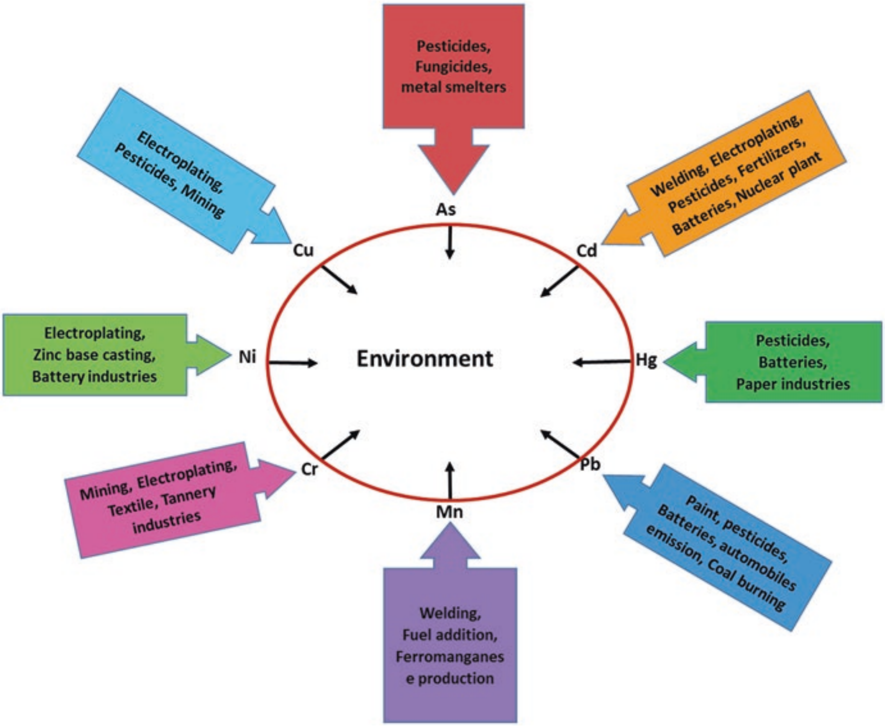

Fig. 2.1 Sources of heavy metals in the environment. (Modified from Paul 2017)

become a global problem. Appropriate prevention measures need to be seriously implemented to avoid metal contamination in food. People consume food on the basis of their social and financial capabilities. The situation in developing countries are more vulnerable, as low-income individuals are unable to afford the good quality food and the right amount of nutrition. The national and international regulatory bodies should attempt to reduce the urban pollution load to reduce contamination in fruits, vegetables, and cereals. The contamination of following heavy metals are most common in foodstuff.

2.1.1 Lead

Lead is a naturally occurring element and is the most commonly used element after iron. No significant biological function of lead in a human being is known. Exposure of lead can be from the air, water, dust, food, and consumer products (Lead poisoning and health 2016). Exposure of high concentration of lead can be poisonous and can affect the health of all ages of peoples. Lead can more severely affect vulnerable population especially infants, young children, pregnant women, etc. Lead contamination in food stuffs is mainly caused by the application of chemical fertilizers and pesticides or through contamination of soil by sewage and industrial effluents. Once in the food chain, lead can easily accumulated in the human body, which may result in acute poisoning (Tajkarimi et al. 2008). The three main body systems, i.e. nervous system, hematopoietic system, and renal system, are highly sensitive to this metal (Naseri et al. 2015; Zahir et al. 2005). Lead can affect many organs and functional systems of the body; further high exposure can be carcinogenic, damages the brain, and causes miscarriage in pregnant women. Regulatory limits of lead in air and water as per EPA are 0.15 micrograms per cubic metre (for air) and 15 ppb in drinking water.

2.1.2 Cadmium

Cadmium makes up to 0.1 ppm of the earth's crust (Wedepohl 1995). It is a toxic heavy metal present naturally in the environment. Primarly cadmium contaminal occurs from mining, smelting, and refining sulphidic ores of zinc as well as from dust generated by recycling iron and steel scrap (Ayres et al. 2003). Phosphate fertilizers contain varying amounts of cadmium up to 300 mg/kg, and therefore, application of high amount of chemical fertilizers in agricultural soils results Cd contamination in agricultural lands (Grant and Sheppard 2008; Jiao et al. 2004). The high level of cadmium contamination generally occurs in the industrial areas. A significant exposure of cadmium to human beings is also occure by cigarette smoking. Resident residing near hazardous waste dump sites or industries which emit Cd into the ambient air has a potential chance of exposure through respiration of such contaminated air. The Cadmium contamination into the groundwater, soil, and crops which has resulted in adverse health effects such as hypertension, mutagenesis, carcinogenesis, and kidney lesions (Binns et al. 2003). The main culprit of Itai-itai disease is cadmium exposure which is characterized by severe pain in spine and joints. The cadmium poisioning can affect calcium metabolism and results brittle bone and kidney failure (Abbasi 2015). Cadmium poisioning in mass level was first reported in Japan which was occurred due to consumption of contaminated rice grown in river water contaminated by cadmiun due to release of mining spealage. The concentration of cadmium should be under 5 ng/m^3 in the atmosphere, 2 mg/kg in the soil, 1 μg/L in freshwater, and 50 ng/L in seawater (Rieuwerts 2015).

2.1.3 Chromium

Chromium is a toxic heavy metal that occurs in the environment in oxidation states. Chromium(III) in traces, is an essential nutrient for human biological process. Both chromium(III) and chromium(VI) are stable elements, while chromium(VI) a very toxic form and also carcinogenic i.e. cancer-causing for human beings (Thompson et al. 2012; Costa and Klein 2006) and teratogenic i.e. malformations in a foetus (Xia et al. 2016). The release of chromium is mainly occurs through industries.

such as from tanning, mining, electroplating, and textile industries (Ajmal et al. 1996; Moncur et al. 2005). Coal and oil combustion also leads to release of Cr in the environment (ATSDR 2000). The exposure of chromium to human may be through oral, dermal, and/or through inhalation. The oral intake of these heavy metals is also occurs from contaminated wells (EPA 1998). Exposure of chromium may cause several types of diseases i.e. mouth ulcer, indigestion, acute tubular necrosis, vomiting, abdominal pain, kidney failure, and even death (Beaumont et al. 2008). The maximum concentration level of chromium in water supply should be 0.05gm/L according to Indian standards (Benazir et al. 2010).

2.1.4 Arsenic

Arsenic is a naturally occurring element and is present in water air and soil. Arsenic pollution and toxicity are one of a major global problem. Contamination of arsenic is occure by natural geological sources which results in groundwater contamination. Arsenic contamination also occur due to human activity like mining and industrial processes. It is present in both forms, i.e. organic and inorganic. The major use of As is in the alloys of lead, i.e. car batteries and ammunition. Arsenic is also widely used as a wood preservative. Leaching of As into the groundwater can be through rocks, soil, and pesticides. Volcanic eruptions and mining activities can also lead to the release of As in the environment. Groundwater contamination of As is a global problem. A higher level of As is usually found in the aquifers and less in surface water. Dietary intake of even a very small amount (less than 5 mg) could result in vomiting and diarrhoea (Kingston et al. 1993). Lethal dose of As ranges from 100 to 500 mg which results acute poisoning (Schoolmeester and White 1980). The permissible limit of As in drinking water is 0.01 mg/L as given by the Bureau of Indian Standards.

2.1.5 Mercury

Mercury is the only metal that is present in a liquid state at standard temperature and pressure and is a poor conductor of heat a fair conductor of electricity compared to other metals (Hammond 2005). It is also known as hydrargyrum (Random House Webster's Unabridged Dictionary 2014), a shiny metallic liquid present in trace amount in igneous and sedimentary rocks. Mercury exposure to human beings occur through ingestion, inhalation, and skin contact. Studies have suggested that mercury vapour inhalation can cause immune system disorders, kidney dysfunction, infertility, adverse effects on the foetus, heart failure, and Alzheimer's disease. Exposure to mercury can cause serious health problems and a threat to the early stage of development in children. Toxic effect of mercury is reported in the nervous, digestive, and immune systems and on the lungs, kidneys, skin, and eyes. People are often exposed to mercury in the form of organic mercury, that is, methylmercury, generally from consumption of fishes and shellfish from mercury contamination in seas and oceans (report by the WHO). Also, mercury exposure via food can be through the consumption of contaminated rice and other food stuff. Mercury poisoning can cause Minamata disease, which is a neurological syndrome. As per recommendations of EPA and Food and Drug Administration (FDA) mercury concentration should be less than 2 ppb in drinking water, less than 1 ppm in seafood as per guidlines of the Occupational Safety and Health Administration (OSHA). The organic mercury should be 0.1 milligrams of per cubic metre of workplace air, and the exposure should not be more than 0.05 milligrams per cubic metre of metallic mercury vapour for 8-h shifts and 40-h work week (OSHA).

2.2 Source of Heavy Metals

Metallic chemical elements that have higher density and higher atomic weight or mass and are capable of causing an adverse effect on human and environment in low concentrations due to its toxic and poisonous effect are generally termed as heavy metals (Lenntech 2014). These are naturally occurring elements found in the earth and rocks. Due to some of the natural but mainly due to anthropogenic activities, once these metals are released, get concentrated in the plants, animals, and human tissues via inhalation and ingestion and sometimes through misshandling or accidents. Chemical elements such as lead (Pb), cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), copper (Cu), iron (Fe), and the platinum (Pt) group are considered as heavy metals.

2.2.1 Natural Source of Heavy Metals

Metals have been present in the earth from the beginning of the earth's formation, i.e. billions of years ago (Dalzeil 1999) by the natural process of the biogeochemical cycle. The weathering process of underlying bedrocks is the result of naturally occurring heavy metals in the soil. Mendip region's soil (Great Britain) has been found to be heavily enriched with lead, zinc, and cadmium due to mineralized veins and high concentration of metal deposits in the bedrock (Fuge 1991). Bedrock weathering with slightly elevated heavy metal concentration can result in metal enrichment during soil formation process (Blaser et al. 2000). Both natural and anthropogenic sources are the main causes of increasing heavy metal contamination in the environment. Sources of natural cause can be from windblown soil particles, volcanic eruptions, forest fires, biogenic sources, and sea-salt sprays (Muhammad et al. 2011). Windblown dust naturally emitted is often from the industrial origin (Fig. 2.2).

Fig. 2.2 Natural sources of heavy metals in the environment

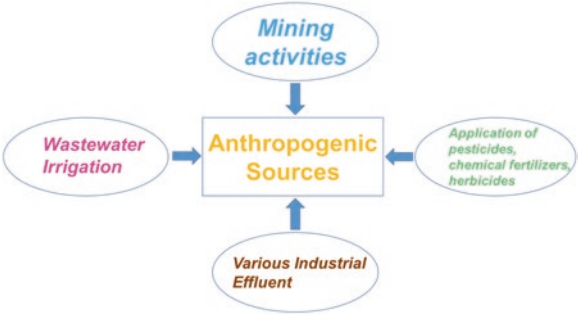

Fig. 2.3 Anthropogenic sources of heavy metals into the environment

2.2.2 Anthropogenic Sources

The anthropogenic sources of heavy metal contamination are mining activities; application of pesticides, chemical fertilizers, and herbicides; irrigation of crop fields with contaminated water released by small industries and tanning industries; and use of municipal waste as fertilizers (Alloway and Jackson 1999; Srivastava et al. 2018; Sarkar et al. 2018). Applications of mineral fertilizer that contains trace amount of heavy metals are some of the major sources of heavy metal contamination in the food that we consume (Gray et al. 1999). Other anthropogenic activities are the disposal of waste in farmland (Merian et al. 2004; Srivastava et al. 2015, 2016), traffic emission, use of lead as an antiknock in petrol, cigarette smoking, metallurgy and smelting, aerosol cans, sewage discharge, and building materials (Nriagu 1990; Srivastava et al. 2017) (Fig. 2.3).

2.3 Food Contamination by heavy metals

During the process of food production, packaging, and transport from 'farm to fork', there are several possible ways by which the food gets contaminated by various toxicants including heavy metals. Contamination has such potential to migrate into the food and become bioavailable after oral intake. The largest source of food contamination occurs through food contact materials. Plastics, printed papers, and boards are some of the basic food contact materials. These food contact materials are cheaper, durable, and non-porous which makes it primarily the most commercials' container for storage of food.

As the process of contamination from its primary source was carried in the environment, then contamination level and the concentration of heavy metals transferred into the food chain and food web through different trophic levels. Heavy metals present in the soil, air, and water get accumulated in the plants or animals, and ultimately reaching into the foodstuff. The contamination through human activities, as a result, can affect a large geographical area affecting the environment and human health. The bioaccumulation of heavy metals and their transfer occur from lower trophic level to the higher trophic level. The concentration is always higher in the higher trophic level.

A study was conducted in Ghana reported that irrigation with water contaminated with Cd and Pb resulted in the accumulation of these heavy metals and showed significant concentration in carrot, cabbage, and lettuce (Odai et al. 2008). The scientists from all over the globe are evaluating the daily intake of such substances from food and their accumulation rate in the human body and are making cautious effort to regulate and control these substances with the help of government and NGOs. Appropriate efforts and strategies are being made to combat and minimize the heavy metals to enter our food chain. Studies have been conducted in indigenous people's traditional diet which has been found to be contaminated by organochloride through marine fish and mammals in their diet especially in New Zealand (Stewart et al. 2011). Certain research has revealed that indigenous communities have elevated heavy metal contamination in the traditional diet (Hoekstra et al. 2005; Johansen et al. 2004; Odland et al. 2003; Van Oostdam et al. 1999, 2003). In the aquatic food chain, heavy metals easily get accumulated in the animals having comparably high lipid contents. An example of an aquatic animal, i.e. eels which are rich in lipid and are at the top of the food chain of New Zealand, were found to have comparably higher accumulation of contaminants (Stewart et al. 2011).

High concentration of heavy metals in the marine animals have drawn the interest in contamination in public food supply, especially in fish (Tariq et al. 1993; Kalay et al. 1999; Rose et al. 1999). Environmental scientists and toxicologists are putting efforts to measure such contamination in our food chain and have estimated the dietary intake and accumulation in our body. There are many regulatory agencies have specific recomendations for the acceptable limits of such contaminants. Heavy metals in food may be found naturally or by environmental contamination or during the process of making the food (Steve Hall 1995; Voegborlo et al. 1999). Aquatic ecosystems near the industries have a significantly greater amount of heavy metals. Even a small concentration of these heavy metals in the ocean has a significant effect on biological productivity. Heavy metal once released in the aquatic ecosystem, it can be distributed and accumulated in the different part of the aquatic biota including flora and fauna. Therefore, most of the species of flora and fauna act as an environmental indicator in the environment and hence monitored for the assessment of environmental risk and pollution load (Jorgenson and Pedersen, 1994; Widianarko et al. 2000). Fish are on the top of the consuming food in the aquatic system (Dallinger et al. 1987). Other than occupational exposure of heavy metals, consumption of fish is the largest source of mercury intake in our diet.

Heavy metals such as methylmercury and mercury have been reported in different aquatic organisms (Pandit et al. 1997). Accumulation of organometallic compounds in superior organisms is due to the high affinity to –SH groups of lipid tissues and proteins in organisms (Pongratz and Heumann 1999). The most common form of mercury found in the environment is methylmercury which is converted from ionic mercury to organomercury and has a potential of causing a hazard (Hintelman et al. 1993; Tripathi et al. 2003). Methylmercury can cause toxicity in the brain, especially in the central nervous system, which may occur at very low doses i.e. 3.0 μg/kg in humans (WHO 1976). Inorganic arsenic contamination in food has also been a potential hazard to human health because of its carcinogenic effect on human as well as deleterious effects on the urinary bladder, lung, and skin. Studies have revealed that due to anthropogenic activities, higher concentration of arsenic is found in aquactic ecosystems. Therefore, the arsenic exposure to human beings is mainly occur via ingestion of contaminated seafood and drinking water.

2.3.1 Application of Fertilizers and Pesticides in a Crop Field

Due to the rapid increase in the human population, the demand for food in the society has also accelerated, which has increased the demond of application of a huge amount of fertilizers to increase the crop yield. In the same manner, application of insecticide has increased many fold to protect the crops from the pest. Insecticides are not only used in agriculture, but also in the pharmaceuticals and other, industrindustries, and consumer products. Insecticides are claimed to be a major factor behind the increase in the twentieth-century agricultural productivity. Being toxic in nature, most of the insecticides have the potential to significantly alter ecosystems. Most of the pesticides get concentrated in the ecosystem spread along the food chain. A report by Islam et al. (2018) in Bangladesh stated that concentration of Cu, Cr, As, and Cd was higher than the irrigation water quality standard given by FAO. They also identified the problem and concluded that it was due to polluted water and the use of agrochemicals in the agricultural field.

2.3.2 Contamination by Anthropogenic Activities

Heavy metals like arsenic, lead, mercury, and cadmium are toxic and cause neurological problems in developing children (WHO 2017; Tchounwou et al. 2012). Anthropogenic activities like the burning of fossil fuels and mining activities are some of the major of these metals as these metals contaminate the agricultural soil by aerial deposition (Pollution 2007). Subsequently, the plants take up the metals from their root system from the soil resulting in contamination of vegetables and fruits. Urban farming and gardening practices also have contamination in food due to urban pollution.

2.3.3 Food Processing and Packaging

After harvesting, the crops need to be stored appropriately. The food is usually stored in the plastic containers because it is cheap, and easy to handle. But when the food gets in contact with the plastics, some of the chemicals present in the plastics, get leached out and contaminate the food (Radford 2019). Even in the contianers madeup of inert materials like ceramic, glass, the chemicals present in these materials can migrate to the food from their inner surface of the containers. Non-inert materials like adhesives, labels, coating, and inks can also contaminate the food. Canned food is often less nutritious than fresh or frozen food and sometimes get contaminated during storage and transpost (Muncke 2016). Sulphites are common preservatives used in various fruits which has adverse effects in the form of palpitations, allergies, headaches, and even cancer in the human beings. Nitrates and nitrites are used as curing agents in meat products. It gets converted into nitrous acid when consumed and is suspected of causing stomach cancer. Benzoates are used in foods as antimicrobial preservatives and have been suspected to cause allergies, asthma, and skin rashes. A serious issue arose when cooking the meat in grills as directly cooking meat and other food products with flames of gas, charcoal, and combusting wood, there are posibilities of getting it contaminated as charcoal and wood emits chemicals during burning known as polycyclic aromatic hydrocarbons (PAHs). PAHs are potential carcinogens and may cause severe damage to the skin, liver, and stomach in the long-term exposure.

2.3.4 Adulteration in Food

Adulteration in food is a common practice by the food producer so that they can increase their profit margin. Some of the common practice in food adulteration is adding water, chalk, urea, caustic soda, and skimmed milk in milk. It is also easy to adulterate oil and fats, which is undetectable. Ghee is often mixed with hydrogenated oils and animals fats. Adulteration in food grain includes the mixing of sand or crushed stone so that the finished food grain product increases the weight. In some vegetables, synthetic colours are used to give it a natural appearance to the consumers. Cheap, synthetic, and chemical colour flavours are used in some food products which are dangerous and may cause allergies to some of the consumers. Such adulteration practices should be strictly monitored and abandoned by the food quality regulatory organizations, and also the people should be made aware as what they are consuming (Radford 2019).

2.3.5 Contamination of Agricultural Soil and Crops by Irrigation of Wastewater

Rapid growth in the human population, industrialization and modern agricultural practices have accelerated the rate of contamination of heavy metals in the environment. Heavy metal contamination in irrigation water and soil from numerous activities such as irrgation of crops from domestic wastewater and industrial effluents are the major concerns. Further, release of untreated effluents in the water bodies, streams, lakes, and the river leading to heavy metal contamination in aquatic bodies and when such water is used for irrigation, agricultual soil and crops get contaminated. Even heavy metals leaching through the contaminated soil and industrial waste can contaminate the groundwater aquifers. Arsenic pollution in groundwater is the major issues in the globe.

The availability of freshwater resources are very scarce which is getting reduced every year and many part of the world are faciting water crisis even for the drinking purposes and some of the counties would soon face water scarcity in the near future. Throughout the world, farming depends on river water, lakes, and streams for irrigation. Groundwater is also an alternative water resource, but due to rapid uses, the water table is declining and would be deficient even for drinking purposes. With the increasing use of mineral fertilizers for high production of crops for maintaining the demand of food, unintentionally the groundwater aquifers are getting polluted especially for the nitrate contamination is increasing in drinking water (Schroder et al. 2004; Camargo and Alonso 2006). This is same in the case of almost all the developed and developing countries. In the past, soil contamination was not considered as an environmental problem compared to the air and water pollution. But in recent times, the soil contamination has become a major environmental problem.

The major problem with soil contamination is that, it takes a longer time to remediate (Wood 1974) and is difficult to reverse the effect of numerous types of contaminants through dilution or by self-purification and other techniques. whereas it is comparably easy to manage the water pollution by managing the point sources of pollution. Plants grown in contaminated soil car accumulate heavy metals in their tissues and act as bio-sinks for these heavy metals (Bhatia et al. 2001). Heavy metal contamination in water due to natural weathering of rocks is unpreventable however, contamination due to human activities can be managed up to some extent.

Wastewater use in irrigation is increase many folds in past few decades due to unavailability or shrinking of freshwater resources. The use of wastewater can conserve freshwater, reduce pollution in available water resource, and also provide micronutrients, organic matter, nitrogen, phosphorus, etc. (FAO, 1992; Murtaza et al. 2010; Hanjra et al. 2012). However, heavy metals and some of the organic contaminant not get removed during the conventional wastewater treatment, which subsequently ends up in the agricultural soil through irrigation water and ultimately to the human food chain (Fytianos, 2001). According to a study, consumption of heavy metals via food, milk, and drinking water in India was higher than that of the limits set by the WHO and FAO (2007). Heavy metal contamination in human food chain is shown in the Fig. 2.4.

2.4 Accumulation and Toxicity of Heavy Metals

The heavy metals has been proven to cause health-related issues and a major threat to the exposed population. Due to its ubiquitous nature and tendency to remain in the environment for a long time, thus get accumulated in different component of the environment and poses toxic effects (Gilbert and Weiss, 2006). Heavy metal exposure and toxicity can be divided into chronic and acute toxicity. Once metal contamination occure in the biological system, certain metals can combine with the sulfhydryl group, inhibiting various enzymes and processes in the biological process, due to it's high-affinity properties (Jan et al. 2015). Chronic exposure of heavy metals can induce neurotoxicity and hepatonephrotoxicity (Caito and Aschner 2014).

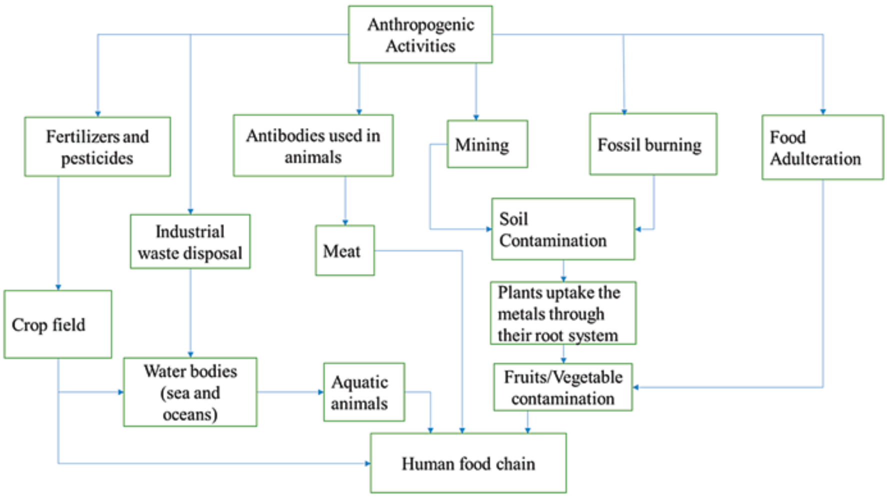

Fig. 2.4 Flow chart of heavy metal contamination in human food chain

2.4.1 In Agricultural Crops and Plants

The pathway by which the heavy metal ions enter through the food crops is from the root system of the crops, i.e. apoplast and symplast movements. These two movements are two different pathways by which water and metal ions pass through the root hair via the root cortex to the xylem. In the apoplast movement, more ion and water are transported through the apoplastic pathway (inner cellular space) in the cortex, whereas in symplast movement, water and ion are mainly delivered through the symplastic pathway beyond the cortex. Heavy metal movement occurs generally in the symplastic pathway, i.e. through crossing the plasma membrane (Peer et al. 2006). Further, the metal ions are facilitated inwards by the electrochemical gradient (Raskin et al. 1994). When the metals reach the xylem, the metal transport is mediated by the membrane transport protein (Thakur et al. 2016). Arid and semi-arid regions with short wet seasons and long dry seasons, rely on unconventional water resource and are being used to fulfil the increasing demand for food for the society. Vegetables/crops grown in wastewater irrigation-contaminated soil accumulate a significant level of heavy metal concentration than that grown in soils irrigated with freshwater (Balkhair and Ashraf 2016). A study by Khan et al. (2008) concluded that irrigation with untreated irrigation water increases Pb, Ni, and Cd concentration in the crops and poses an adverse effect on the health of humans. Leafy vegetables can accumulate comparably a higher concentration of heavy metals when grown in a site contaminated by heavy metals that are absorbed mostly in the leaves of the vegetable (Jassir et al. 2005). Vegetables like cauliflower, spinach, and cabbage can even grow well in a high level of heavy metal-contaminated soils and wastewater irrigation (Cobb et al. 2000), whereas some of the vegetable like radish is more sensitive to sewage water (Kapourchal et al. 2009).

Heavy metal uptake by food crops depends upon soil physicochemical characteristics and plant species (Zhuang et al. 2009). Bai et al. (2010) reported that cultivation history is an important factor related to the accumulation of heavy metals, particularly of Cu, Pb, and Zn. Heavy metal uptake in crops majorly depends on the temperature, moisture, pH, organic matter, nutrient availability, plant species and their uptake potential, or soil-to-plant transfer factors (Tangahu et al. 2011; Khan et al. 2008).

Elevated heavy metals in soil can result in a decline in soil productivity; lower the development process which are vital for plant growth like photosynthesis, mitosis, and water absorption; and lead to stunted growth of plants/crops (Bhattacharyya et al. 2008). Use of municipal waste, sewage sludge in the agricultural field is a general practice in developing nation worldwide to lower the cost of fertilizers. However, applications of waste and sludge may contaminate the soil and groundwater quality and may increase poisoning in the food chain.

2.4.2 In Aquatic Animals

Burning of coal, smelting, and industrial waste disposal into the seas and oceans are the main causes of pollution in ocean water (Global Mercury Assessment 2013). Due to this, the aquatic life in the seas and oceans are severly getting affected. Mercury has been the main contaminant in fish, inorganic and organic mercury disposed into lakes and rivers may be transformed into methylmercury, and the mercury levels found in fish, even from ‘non-contaminated’ areas, are higher than in most other foods. These get absorbed in algae and get biomagnified by the large fish and ultimately get into the human food (Mercury Levels in Commercial Fish and Shellfish 1990–2012).

A report from Guallar et al. 2002 [85] stated that high contamination of metals in fish have an adverse effect on many vital organs of human beings. As per a report from Lake Ontario, decline in woman fertility was observed due to the consumption of contaminated fish (Buck et al. 2000). Similarly, persistent organic compound is found in the aquatic environment, get accumulated in the fatty tissues of fish and passes through the food chain to higher trophic level (Håstein et al. 2006). Due to consumption of fish contaminated with the organochlorine compounds presence of such compounds has been reported in the human lipids and tissues and even in breast milk in women in the countries like India, Japan, and Argentina (Muñoz de Toro et al. 2006; Tsukino et al. 2006; Someya et al. 2010). Organic mercury has higher toxicity than inorganic mercury because of it's high solubility in lipids and low rate of elimination which causes bioaccumulation in the organisms (Díez 2009). In the aquatic system, heavy metals exposure to the organisms occurs through their food along with water (Phillips 1995). It was observed that fish accumulate comparably higher concentration of metals when the number of phytoplanktons are high in the region than the areas where the dencity of planktons are low. Heavy metal accumulation in the flora and fauna increases over the time. Summary of the concentration of heavy metals in agricultural soil irrigated by wastewater is presented in the Tables 2.1 and 2.2 provide a summary of heavy metals in various types of vegetables.

Table 2.1 Summary of the concentration of heavy metals in agricultural soil irrigated by wastewater

Type of water	The concentration of metals (mg/Kg) in soil irrigated with wastewater										Country	Year
	Cd	Cr	Cu	Pb	Ni	Fe	Mn	Zn	As	Hg		
Domestic wastewater												
Urban wastewater		118.90	39.44		39.75			50.07			Spain	Martínez–Cortijo and Ruiz–Canales (2018)
Wastewater	1.76	42.19	32.68	12.04			277.62	68.75			Iran	Cheshmazar et al. (2018)
Leather industry	0.45	976		50.32					1.94		Bangladesh	Mottalib et al. (2016)
Gold mining	2.867		106.10	723.50				452.90	15.81	12.195	China	Xiao et al. (2017)
Peri-urban industrial	0.605	57.65	5.405	37.6	88.90		359.55	151.3			India	Chabukdhara et al. (2016)
Smelting	7.52		128.7	1090.0				820.0	903.5		China	Zhou et al. (2016)
Domestic as well as industrial wastewater												
	1.42	63.48	107.65	213.93	34.75			427.80			Spain	Zimakowska– Gnoinska et al. (2000)
	0.78		95.00	23.00	57.00						America	Han et al. (2002)
			65.00	139.00	29.00			140.00			Slovakia	Wilcke (2005)
	13.5	48.5	48	55	29			88.5			USA	Jean–Philippe et al. (2012)
	0.82	2.19	1.20	0.95	4.34			28.24			India	Raju et al. (2013)
	0.34	10.36	9.62	5.17	11.28			11.56			Iran	Sayyed and Sayadi (2011)

Table 2.2 Summary of heavy metals in various types of vegetables

Type of vegetable	Concentration of metal (mg/kg)										Country	Author and year of publication
	Cd	Cr	Cu	Pb	Ni	Fe	Mn	Zn	As	Hg		
Leafy green												
Lettuce	<0.005	0.23	0.505	0.016				0.345	0.005	<0.008	China, Spain	Khan et al. (2008) and Ercilla–Montserrat et al. (2018)
Spinach		2.9	0.09	3.1	3.2			10			India	Chary et al. (2008)
Red amaranth	<0.1	<0.1		1.036	0.840	136.3	5.720	11.305	<0.1	<0.03	Bangladesh	Tasrina et al. (2015)
Beetroot	0.09	0.21		0.58	0.26						São Paulo, Brazil	Guerra et al. (2012)
Cruciferous												
Cabbage		0.23	0.505	0.016				0.345			China	Khan et al. (2008)
Cauliflower	0.014	0.02	0.6	0.03	0.68			5.45			China	Song et al. (2009)
Brussels sprouts												
Broccoli	0.08	0.48		0.93	0.26						São Paulo, Brazil	Guerra et al. (2012)
Marrow												
Pumpkin	0.01	1.45		0.25					0.02		Dhaka, Bangladesh	Islam et al. (2014)
Cucumber			0.38	0.031				1.30			China	Xiu-Zhen et al. (2009)
Italian zucchini	0.04	0.08		0.51	0.25						São Paulo, Brazil	Guerra et al. (2012)
Paulista zucchini	0.04	0.15		0.59	0.23						São Paulo, Brazil	Guerra et al. (2012)
Root												
Potato	0.015	0.03	1.03	0.067	0.054			3.77			China	Song et al. (2009)
Sweet potato	0.14	0.04		0.46	0.18						São Paulo, Brazil	Guerra et al. (2012)
Carrot	<0.1	<0.1		0.304	<0.1	8.824	1.257	1.206	<0.1	<0.03	Bangladesh	Tasrina et al. (2015)

Yam	0.06	0.20		0.72	0.20						São Paulo, Brazil	Guerra et al. (2012)
Edible plant stem												
Celery	0.05	0.14		0.47	0.19						São Paulo, Brazil	Guerra et al. (2012)
Asparagus bean	0.013		1.999	0.07				6.682	0.047		South China	Zhou et al. (2016)
Kidney beans	0.010		1.310	0.033				5.669	0.05		South China	Zhou et al. (2016)
Allium												
Onion	0.02	0.07		0.49	0.06						São Paulo, Brazil	Guerra et al. (2012)
Garlic	0.09	0.29		2.50	0.42						São Paulo, Brazil	Guerra et al. (2012)

2.5 Human Health Risk of Heavy Metals

Heavy metal toxicity is generally by cadmium, chromium, lead, mercury, and arsenic, and their exposure is commonly occure mainly through consumption of contaminated foodstuff, and through the contaminated environment. Toxicity of these heavy metals results from sudden, acute, or chronic exposure over a period of time. Symptoms of heavy metals toxicity depend upon metal absorbed, metals involved, and age of the person exposed to these metals. Cadmium particles or fumes can cause acute pulmonary effects and even the death of an individual (Seidal et al. 1993; Barbee and Prince 1999). Kidney damage is generally due to the heavy exposure of cadmium. Several reports have suggested that the kidney damage or bone effect in human can arise even from the exposure of a lower concentration of cadmium. High exposure of cadmium for the longer period can lead to skeletal damage, which was first recorded in Japan in the 1950s and it was named as ita-itai disease. This disease was occurred due to exposure through consumption of cadmium contaminated rice grown on a field irrigated with the contaminated water. The International Agency for Research on Cancer (IARC) has grouped cadmium as a human carcinogen (group I). Cadmium exposure can also cause prostate cancer.

Inorganic mercury acute poisoning can lead to lung damage, while chronic poisoning can cause neurological and psychological disorders, such as restlessness, tremor, changes in personality, anxiety, depression, and sleep disturbance. These symptoms are reversible only when the exposure has stopped, and the same can be observed for metallic mercury which causes kidney damage. Methylmercury poisoning can last from 1 month or longer even after acute poisoning, and it's main symptom is the damage of nervous system. Exposure of a higher dose of methylmercury can cause death of a person. Minamata disease was recorded due to dietary exposure of fish contaminated by methylmercury. The contamination of methylmercury in fish occurred due to the discharge of mercury in the water bodies. In the early 1970s, a similar incidence was occurred in Iran, which caused the death of around 10,000 people due to the consumption of baked bread which was prepared from mercury-contaminated grains.

Lead is also get accumulated in liver and kidney of aquatic animals; consuming this lead-rich diet can cause an unacceptably high level of lead in the human body. Lead contamination in food also occur through food containers like ceramic vessels with lead glaze, storage in lead-soldered cans and leaded crystal glass. Headache, irritation, and abdominal pain are some of the acute symptoms of lead exposure. Sleeplessness and restlessness are some mental disorders which are caused by lead encephalopathy, and children may also suffer from concentration loss, learning difficulties, and behavioural disturbances. Acute confusion, psychosis, and reduced consciousness are observed in adults who may suffer from lead encephalopathy. Lead is classified as a 'possible human carcinogen' by International Agency for Research on Cancer (IARC), in 1987. The upper limit for blood lead for adults is 10 μg/dl (10 μg/100 g) and for children, 5 μg/dl has been set by the Centers for Disease Control and Prevention (USA) (ACCLPP 2012; CFR USA 2005). The evidences from previous studies has revealed that lead poisoned people may suffer from lung cancer, stomach cancer, and gliomas (Steenland and Boffetta 2000). In the most developed nation, over 540,000 people have died due to the exposure of lead in the year 2016 (Lead poisoning and health 2016).

Acute toxicity of inorganic arsenic intake in large amount can cause gastrointestinal symptoms and disturbances in the cardiovascular system and central nervous systems and may lead to the death of an individual. Arsenic encephalopathy, bone marrow depression, polyneuropathy, haemolysis, hepatomegaly, and melanosis are also observed due to arsenic poisoning. Black foot disease in Taiwan is caused by drinking water contaminated by arsenic which damages the lower limbs resulting in progressive gangrene. A report from WHO on arsenic exposure via drinking water suggests that it may cause cancer in the lungs, kidney, bladder, and skin as well as precancerous lesions in the skin (WHO 2001).

Hence, these heavy metals have the potential to cause disease, cancer, or even death of the person if exposed of heavy metals through diet, inhalation, and/or dermal exposure. The exposure to heavy metals and its toxicity to human beings is one of the major issues for regulatory bodies, organization, and government bodies. The chemical toxic agency should provide ways by which such exposure can be minimized and also provide appropriate tools and techniques to reduce the level of heavy metals in the environment and prevent these metals from reaching it into the human, animals, and the environment in the future.

2.5.1 Carcinogenic Risk Due to Heavy Metals

A recent study that was carried in Palestine by Al-Khatib et al. (2019) predicted that the local residents especially children might have a higher chance of developing cancer due to the presence of Mg, Ba, Fe, Sr, K, Na, and Mg, and their values were greater than the standard limits, i.e. $>10^{-6}$. High level of groundwater contamination near the industrial waste site and municipal solid waste dump site due to poor management was reported in Chandigarh, India (Ravindra and Mor 2019). This study revealed that deeper aquifer was less contaminated than the shallow aquifers. The shallow aquifers are generally used for drinking and irrigation purposes which might directly or indirectly exposed human beings to those of the heavy metals.

2.5.2 Noncarcinogenic Risk of Heavy Metals

A recent study conducted in Iran and revealed that heavy metals like Zn, Fe, Al, Pb, Ni, Cd, Mn, As, and Cr were more accumulated in the medicinal plants than herbal plants and only Hg and Cu were found to be higher in herbal plants and its target hazard quotients (THQ) were less than 1 which is considered to be safe for consumption (Kohzadi et al. 2019). Fluoride contamination in Iranian drinking water was estimated to be low and does not had any carcinogenic risk for both adults and children, but fluoride contamination in food and air was high and had significant effect on human health (Keramati et al. 2019). Heavy metal contamination on crayfish, meat, fish, and cowskin was estimated in Nigeria, and it was found that the hazard index of raw, smoked, and cooked meat showed the greater noncarcinogenic adverse health effects (Taiwo et al. 2018). A study conducted in India also reported noncarcinogenic risk due to high arsenic contamination in Indian rice (Sharafi et al. 2019).

2.6 Pathway/Exposure of Heavy Metals

Heavy metal exposure to human beings is often from ingestion, dermal exposure, and inhalation (Asaduzzaman et al. 2017; Li et al. 2017). The exposure of heavy metals is usually occurred mainly through the contaminated drinking water and food. Mercury accumulation in human tissues has higher concentration through consumption of aquatic organisms, i.e. seafood, fishes, etc., in the form of methylmercury (Horvat et al. 2003). The main source of mercury intake in diet of the population is from fish as stated by Boudou et al. (2005).

2.6.1 Ingestion

The occurrence and level of contamination, chemical forms, and metal solubility are some of the factors affecting the absorption of trace metals through the gastrointestinal tract. Ingestion is the primary route of heavy metal intake through diet, and it contributes up to 90% of daily dietary intake compared with inhalation and dermal exposure (Loutfy et al. 2006). For example, arsenic exposure is through food and water, and the daily intake ranges from 20 to 300 μg/day (WHO 2010) depending upon the food type, food processing, and agricultural conditions (IARC 2012). The heavy metals are absorbed and accumulated in leafy vegetables (Arora et al. 2008). Exposure of chromium from food is through meat, molluscs, and crustaceans (U.S. EPA 1998). Kusiak et al. in 1993 have reported that even Cr (III) causes oral toxicity in humans.

2.6.2 Inhalation

Inhalation of heavy metals is considered another pathway of occupational exposure. In the metal plating and some of the other industries, chromium exposure occurs in both forms i.e. Cr(III) and Cr(VI). During inhalation, the Cr(III) gets absorbed in the tissues of the lung due to the reduction of Cr(VI) to Cr(III) (Flaherty, 1996). Chromium is responsible for wheezing, coughing, asthma, and other respiratory diseases (Langard, 1980). The Cr(IV) can even cause cancer in humans even via inhalation route and is classified as carcinogenic material (group 1) by international nodal agencies (IARC, 2012; Waseem and Arshad 2016, 198). Mercury present in the gaseous state, contributes to 80% of the atmospheric mercury (Wang et al. 2004).

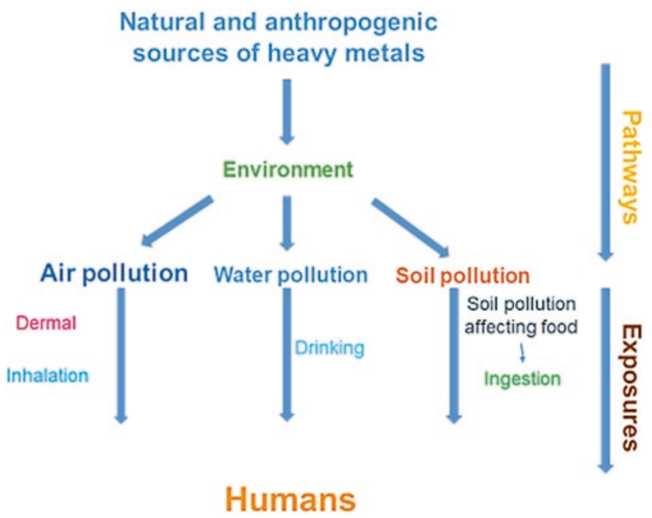

Fig. 2.5 Pathway/exposure of heavy metals in human beings and in the environment. (Modified from Thompson et al. 2012)

2.6.3 Dermal Exposure

The dermal exposure of heavy metals usually occurs when the large surface area of the skin get in to the contact of metal laden dust and fine particles. These small particles sometimes get deposited into the dermal layers of the skin and reached to the circulation system (Li and Zuo et al. 2013, Keshavarzi et al. 2015). The skin is the primary and effective barrier for the absorption of any substance, therefore, only few of the metals that have the ability to penetrate through the dermal layers of the skin, get absorbed. A report by Brandão and Gontijo (2012) stated that nickel metal exposure through the skin has become sensitive to human and is causing allergy in children, especially in developed nations. The exposure pathways of heavy metals is presented in the Fig. 2.5.

2.7 Preventive and Mitigation Measures

Mining, industrial process, and other human activities release several types of chemicals and waste containing heavy metals, in to the environment. Then the metals spread in and around the polluted site polluting the nearby areas. To prevent these heavy metals from polluting the area, the primary release of such type of metals or use of heavy metals in the form of pesticides or fertilizers in the environment should be carefully monitored and regulated. Appropriate waste management system should be adapted in mining areas and industries so that the disposal of such heavy metal waste can be prevented so that metals are not released into the environment. The major problem also lies in the disposal of untreated wastewater, sewage water, and industrial effluents into the river and water bodies, which further affects the aquatic ecosystem and also contaminating agricultural soil as well as the food crops once used for irrigation. So proper waste treatment plans should be adapted in industries and disposal of untreated effluents must be stopped. A proper waste disposal can prevent the heavy metals released in the environment.

Apart from preventive measures, sites that are already polluted should be reclaimed and should so that further harm to the environment can be prevented. Some are several mitigative measures that can be adapted to reclaim the polluted sites and bring back its original state. Some of them are as follows.

2.7.1 Excavation

It is the easiest, oldest physical remediation method for reclaiming contaminated soil. It is practised all around the world for the management of contaminated soil. The advantage of these methods is that the contaminated soil is completely removed and the contaminated site is rapidly cleaned (Wood 1997). The disadvantage of excavation is that while removing and transferring the soil from one place to another place, it should be monitored or else if the polluted soil spread by any means, it will contaminate another site. Soil with a large area of contamination requires a large area to be excavated. Therefore, this technique is very costly and time-consuming.

2.7.2 Stabilizing Metals in the Soil

Heavy metal-contaminated soil once excavated moves into another site for the stabilization process. This is another way by which their toxic effect can be reduced or their adverse effect can be minimized within a confined area (in situ). This process does not affect the environment or generate toxic waste; instead it lessens the toxic effect of the heavy metals with the help of added chemicals which can detoxify the pollutant. Adding phosphate fertilizer in the polluted soil can neutralize its toxic effect, especially for the sites contaminated with a high concentration of lead. Some other chemicals are also used to bind with the pollutants released form a mineral make a stable compound which is insoluble in water. These methods immobilizes the toxicants to the food chain, and once the metals biologically unavailable, they are harmless to the environment (Lambert et al. 1997).

2.7.3 Use of Plants

Some plants have special ability to reduce the toxic effect in areas and used in situ remediation of contaminated soil, air, and water and is often termed as phytoremediation (EPA 1998). Phytoremediation has certain advantages and is a widely accepted as a low-cost technique for remediation of the degraded, contaminated site (Schnoor 1997). Disadvantages of phytoremediation are that it takes a bit longer time for remediation. Sites that are contaminated can be revegetated with the help of some of the specific plant species, and this process is called phytostabilization. Plants help reduce wind erosion and soil erosion and also help in reducing the materials spreading from one contaminated site to another site. Another way by which plants can be used for cleaning up contamination is phytoextraction. Some plants have the ability to uptake certain heavy metals and concentrate them into their tissues. These plants can further be harvested and disposed of in safe places without harming the environment. Plants like Indian mustards, alfalfa, cabbage, juniper, tall fescue, and poplar trees have potential to accumulate heavy metals and do not possess any harm to the environment and any living organisms. Indian mustards can cure lead contamination in the soil. A rhizofiltration process is another technique used for remediating heavy metals in water bodies in which the roots of the plants directly remove the contamination with the help of some aquatic plant species or hydroponic methods (EPA 2000). Sunflower plants were used to remove radioactive metals in the water lakes of Chernobyl, which is an example of the rhizofiltration technique.

2.8 Conclusion

Food contamination with heavy metals has become a major problem all over the globe and has an adverse effect on human health and the environment. Heavy metals have been on the earth naturally. However, their release in the environment has been accelerated by human activities leading to pollution in the environment. These pollutants are nondegradable and have reached into our food chain and food web, resulting in abnormalities in the metabolism of humans leading to acute and chronic disease or even death. Local people residing nearby areas of pollution site should be made aware of the deleterious effects of the pollutants released and how that can be a threat to their life. The cultivation and production of food crops near area contaminated with a high concentration of heavy metals must be banned. Due to the scarcity of available freshwater, wastewater irrigation is used as an alternative source for irrigation. Unfortunately, continuous use of wastewater is also a prime cause of heavy metal pollution and contamination of food crops. Pollution in water bodies have also become an environmental concerns because water is the only source of survival for living organisms and the survival depend upon water before prehistoric time. In view of this, rainwater harvesting and watershed management must be adapted to harness the freshwater resource which could be utilized for farming.

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Climate Change Impact on Forest and Agrobiodiversity: A Special Reference to Amarkantak Area, Madhya Pradesh

3

Bhairo Prasad Ahirvar, Shivaji Chaudhry, Manish Kumar, and Pallavi Das

Abstract

Impact of climate change causes many visible changes within an ecosystem and organism. In recent years, biodiversity loss is one of the challenging issues which are affected by climate change. India has a unique climate which supports rich biological diversity. Amarkantak is a holy town situated in district Anuppur of Madhya Pradesh. Some parts of Amarkantak come under Achanakmar-Amarkantak Biosphere Reserve (AABR). It lies between latitude 22°15 to 20° 58 N and longitude 81° 25 N to 20°5E. The biosphere reserve is an origin place of three major rivers of Central Indian region, i.e., Narmada, Son, and Johila and their tributaries. It is home to primitive tribal communities like Baiga, Gonds, Panikas, Kol, and Dhanaur. All these communities are mostly dependent on the forest and agriculture for their livelihood. Last few decades, climate change impacts on the non-timber forest products (NTFPs) and agricultural crops. A finding of the study shows that locals felt a lesser number of rainy days which directly affect crop production of the area. Apart from that, quantity of NTFPs has also declined. Fishery sector of the area is also affected. The climate of the region supports rich diversity of plants and animals' species. Few medicinal plants are now not available in natural forest due to extreme forest fires and overexploitation.

Keywords

Climate change · Forest · Agrobiodiversity · Livelihood · Amarkantak · Madhya Pradesh

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3.1 Introduction

Climate change has great impact on forest and agriculture from last decades. Low-average rainfall and extreme temperature change the production of agricultural as well as nonagricultural crops. Forest and agriculture are livelihood option for most of the communities in India. Forest area is about 33% of the Earth's surface and comprises 66% of all the known terrestrial species. Forests are also rich biodiversity hotspots. Approximately, 50% forest has cleared till now (Rathore and Jasrai 2013). The increased level of CO_2 has led to increase in the growth of some forest. Temperature increases up to 1 °C can cause migration of tree species, pest attack and expansion of invasive species, and forest fires (Rathore and Jasrai 2013). Typically, people living in rural areas are greatly dependent on the variety of forest products along with subsistence agriculture and thus play an important role in their livelihood. The importance of forest biodiversity is directly related to the maintenance of hydrological cycle of watersheds and health of a multitude of ecosystems found throughout the world (Castillo et al. 2014). According to the Food and Agriculture Organization (FAO), agriculture, forestry, and fishery sectors will face changes in productivity levels due to climate change. When biological systems are stressed due to a typical temperature and precipitation regimes, they are more vulnerable to pests, disease, and invasive species. Shifting vegetation and alterations in hydrological regimes are associated with human migration, species range shifts, and land use changes, leading to an increase in human wildlife conflicts. Humans and other biological species are forced into competing for land and resources when natural habitats and forests are degraded due to droughts, floods, and natural disasters in addition to the land use changes driven by deforestation. Climate is one of the major factors that control the global patterns of vegetation structure, productivity, and animal and plant species composition. Numerous plants can effectively reproduce and grow solely within a specific range of temperatures and respond to particular amounts of precipitation and may be displaced by competition from other plants or may fail to survive if climate changes (Chakravarty et al. 2018). The third assessment report of IPCC concluded that recent modeling studies indicate that changes of climate can seriously impact the forest ecosystem. Therefore, climate change could alter the configuration and productivity of both forest and agricultural ecosystem (Chakravarty et al. 2018). Climate change causes directly or indirectly severe effect on agriculture and agrobiodiversity. Climate change affects agriculture throughout the world. According to the fourth assessment report of the IPCC, crop yield losses as a result of climate change will be harsher in the tropics than in temperate regions. This study indicates that 75–250 million people may be affected by water shortage due to climate change. The most affected people would be poor people due to climate change and resultant economic imbalance, that is, they will not able to access food and water. As indicated by CoP 9, numerous relief and adjustment measures past the span of nations and would cause severe resource constraint. Scientific studies in the area of climate change propose that mean annual temperatures will rise by a further 1.5–1.8 °C, although this may vary from region to region. It is expected that the increases will be highest in tropics and subtropical region, and for the predictable cost, there will be extinction of species in large scale, agricultural yield will be lower, and there will be a great change in cropping pattern (Kostchi 2006). Biophysical and socioeconomic factors are main drivers of agricultural response to climate change. Meteorological variables including rising temperature, changing precipitations, and increased carbon dioxide level affect crop production. Socioeconomic factors influence responses to changes in crop productivity, with price changes and shifts in comparative advantage (Parry et al. 2004). Crop yield is also affected by pollinator species. The honeybee, *Apis mellifera*, is by far the most flexible and ever-presently managed pollinator, increasing production to 96% of animal-pollinated crops (Klein et al. 2007). Bees, butterflies, and other pollinators are sensitive to temperature, rising mean temperature, and extreme climate conditions causing extinction of pollinator's species (Rader et al. 2013). The impact of climate change will affect soil nematodes in many ways. Rising temperature directly affects nematode life cycle, as rates of embryogenesis and growth in several nematode species are exponentially related to temperature (Trudgill and Perry 1994; Ruess et al. 1999) Climate change can affect livestock specifically in two way: the quality and amount of forage from grasslands may be affected and there may be direct effects on livestock due to higher temperatures. The number of studies in relation to climate change impact on livestock is few but has good performance (Adams et al. 1998). Extinctions can disrupt fundamental ecological processes (Sodhi et al. 2011). Ongoing environmental change has likewise activated movement and eradication procedures of biodiversity over the globe. Present climate projections indicate that more ecological change will happen in the coming decades (Stocker et al. 2013). Significant dangers to biodiversity incorporate living space change and misfortune, overexploitation, chemical contamination, invasive species, and increasing population. Climate change can affect forest ecosystem causing shifts in vegetations and altering the frequency, strength, timespan, and timing of fire, drought, insect, and pathogen outbreaks. Changes in the climate and atmospheric CO_2 can also affect forest structure, function, and species composition. About 100 million people living in and around forests in India drive their livelihood from the collection and marketing of non-timber forest products (NTFPs). Changes in forestry could have significant implication for biodiversity, traditional livelihood, industry, soil and water assets, and consequently agricultural productivity (Das and Kumar 2019; Shushant 2013). Therefore, the present study highlights on the climate change impact on forest and agrobiodiversity of Amarkantak region. The study also provides the relation to rainfall and production of agricultural and forest produces.

3.2 Climate and Its Influence on Crops of Madhya Pradesh

Madhya Pradesh, a Central Indian state, has a subtropical climate. April to June is considered hot dry summer, whereas July to September is monsoon season, and November to February is considered winter months, that is, cool and relatively dry. Limited work has been done on climate change on Amarkantak area. Mukherji et al. (2016) have studied about impact of climate change biodiversity of Central India;

they included some parts of Amarkantak. Mir and Akhter (2016) reported about climate change impact on major food crops of Madhya Pradesh. He included crops like rice, wheat, soya bean, maize, sugarcane, etc. Ramteke et al. (2015) studied growth and yield response of soya bean to climate change in Madhya Pradesh. Shushant (2013) studied climate change impact on Eastern Madhya Pradesh. The impacts of climate change have been expected to be evident such as increase in water stress, decline in yields from rain-fed grain crops, and increase in number of tremendous weather events such as droughts and floods (Executive summary May 2017). Mohanty et al. (2017) have studied climate change impact on soya bean production.

3.2.1 Direct Mechanism Human Impact on the Biodiversity (Source: Soule and Wilcox (1980), Pimm and Gilpin (1989))

(a) Exploitation of wild living resources
(b) Expansion of agriculture, forestry, and aquaculture
(c) Habitat loss and fragmentation
(d) Indirect negative effects due to introduction of new species by humans
(e) Indirect positive effects due to introduction of new species by humans
(f) Soil pollution, water pollution, and air pollution
(g) Global climate change

3.2.2 Indirect Mechanism

(a) Human social organization
(b) Human population growth
(c) Patterns of natural resource consumption
(d) Global trade
(e) Economic system and policies that fail to assessment the environment and its resources
(f) Inequality in the ownership, management, and flow of benefits from both the use and conservation of biological resources

3.3 Forest and Agriculture in Madhya Pradesh

Madhya Pradesh (MP) has the largest forest cover in India; 27% geographical area of the state is covered by five different forest types, i.e., (a) southern dry mixed deciduous forest, (b) dry teak forest, (c) northern dry mixed deciduous forest, (d) moist peninsular sal forest, and (e) dry peninsular sal forest. Forest of MP has rich diversity of flora and fauna. There are 11 agroclimatic zones in Madhya Pradesh; agriculture is the backbone for the economy of the state which supports 71% of population's income. About 72% cultivated area is rain-fed agriculture. The most affected group in the society is the rural poor people as they still depend on natural resources for their livelihood such as agriculture and forestry (Anonymous 2017). According to a study (Sushant 2013), the availability of percentage of NTFPs has declined in forests of Madhya Pradesh.

3.4 Materials and Methods

The data was collected from both primary and secondary sources. The primary data was collected by using a questionnaire prepared for information related to climate change impact on forest and agrobiodiversity of the region. 100 persons were interviewed from six different places in Amarkantak area. The targeted group was farmers and forest dwellers of Amarkantak area. The questions were related to rainfall, temperature, crop production, forest produces, availability of medicinal plants, and freshwater fishery. Six places, namely, Bharni, Pamra, Kapila Sangam (Amarkantak), Lankatola (Umargohon), Pushparajgarh, and Farrisemar, were surveyed for filling questionnaire, as shown in Fig. 3.1. People's perceptions about crop production in 3 years (2016–2018) were noted through primary survey (questionnaire). The questions were asked relating to impact of rainfall in major crops like wheat, rice, kodo (millet), and soya bean production. The secondary data of rainfall and crop production data of 10 years were collected from 2009 to 2019 from the Department of Land Record Anuppur. The tendu patta (*Diospyros melanoxylon*) production data were taken from the Divisional Forest Office Anuppur.

3.5 Study Area

Amarkantak is a holy town situated in Pushparajgarh tehsil of Anuppur district of Madhya Pradesh. Some parts of Amarkantak come under Achanakmar-Amarkantak Biosphere Reserve. It lies between latitude 22°15′ to 20° 58′ N and longitude 81° 25′

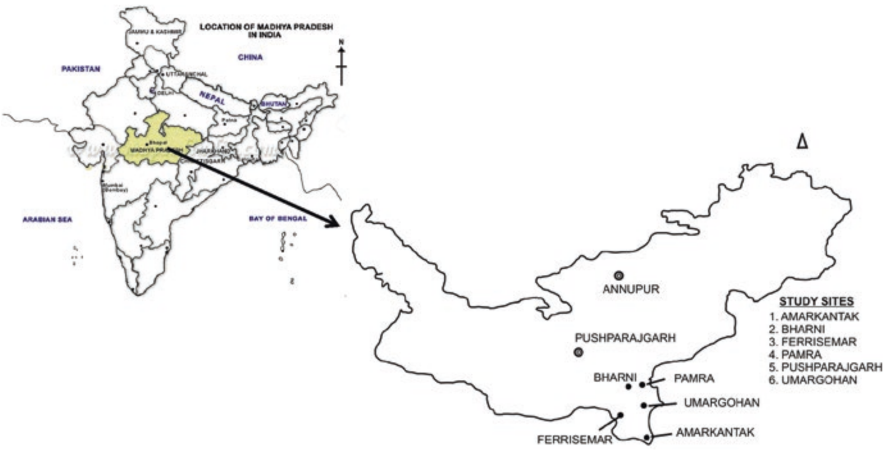

Fig. 3.1 Map showing study area

Table 3.1 Correlation between crop production and rainfall

Year	Rainfall(mm)	Rice	Maize	Kodo	Soya bean	Wheat
2009–2010	920	1540	1120	820	1020	1100
2010–2011	1073	1233	NA	852	967	915
2011–2012	1016	2034	1016	702	1409	1060
2012–2013	1518	2336	1246	402	1477	1141
2013–2014	1963	1974	1355	597	1244	953
2014–2015	1721	2244	1515	613	1368	1496
2015–2016	1031	668	1411	320	387	560
2016–2017	1139	2172	1398	253	1450	786
2017–2018	1349	1754	2893	277	744	3366
2018–2019	1210	1402	2343	547	457	NA
	R^2 value	0.279	0.008	0.019	0.121	0.033

*Crop production in kg/hectare, *NA* not available, *ha* hectare
Source: Department of Land Record Anuppur, Madhya Pradesh

to 20°5′E. The Biosphere Reserve supports three major river systems of Central Indian region, viz., Narmada, Sone, and Johila and their tributaries. It is home to primitive tribal communities like Baiga, Gonds, Panikas, Kol, and Dhanaur. All these communities depend on the forest and agriculture for their livelihood. Amarkantak has 1527 species of identified flora (Anon 2010). There are 518 floral species of food and medicinal value. Most of the geographical area is covered by dense and moderately dense forest. Some portion of land is used for agriculture and the remaining for animal husbandry. Agriculture depends on southwest monsoon. The main crops of the area are rice, maize, chickpea, wheat, and soya bean. Apart from that, the local people also collects forest produces like char (*Buchanania lanzan*), tendu (*Diospyros melanoxylon*), amla (*Phyllanthus emblica*), bel (*Aegle marmelos*), karonda (*Carissa spinarum*), sal leaf (*Shorea robusta*), mohlain leaf (*Bauhinia purpurea*), medicines, dry woods, and fodder.

From Table 3.1, the last 10-year data of crop production showing positive correlation with rainfall. The most affected crop is rice ($R^2 = 0.279$) because rice production is totally depending on rainfall followed by soya bean ($R^2 = 0.121$). Maize is the lowest affected crop ($R^2 = 0.008$). Rainfall is a key phenomenon for any agricultural crop. Every crop and their productivity vary due to amount of rainfall. Crop production and rainfall data show that the production of crops changes with changing rainfall amount.

3.6 Response of Crop Production of Pushparajgarh

Crop production of Pushparajgarh is shown in Fig. 3.2. From field survey, it was found that production of rice in the region has been affected: 20% of the residents stated that rice production during 2016 was poor, 75% of the people stated the production was moderate, and 5% of people stated production was high. In 2017, 30% of the people responded that rice production was poor and 70% stated that production was moderate. According to people's response, the rice production was very

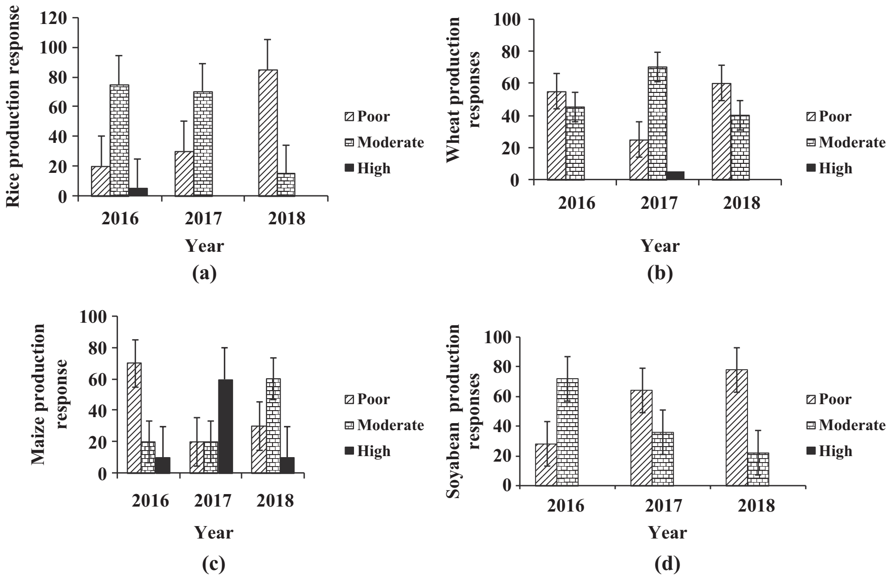

Fig. 3.2 (**a**) Rice production response (**b**) maize production response (**c**) wheat production response (**d**) soya bean production response of Pushparajgarh

poor in 2018. 85% of the people stated that the production of rice was poor and 15% of people responded moderate production. The maize crop of the region is very valuable for the residents. 70% of the residents stated that maize production was poor in the year 2016, 20% stated that production was moderate, and only 10% responded high production of maize. In 2017, maize production was poor according to 20% of the residents, moderate to 20%, and high to 60%. In 2018, 60% of residents stated that maize production was moderate, 30% responded that production was poor, and 10% stated that production was high. 72% of the people stated that soya bean production was moderate, and 28% stated that production was poor. In 2017, soya bean production was poor according to 64% of residents and moderate according to 36% of residents. 78% of the people stated that soya bean production was poor and 22% stated that production was moderate. In 2016, 55% of residents stated that the production of wheat was poor and 45% stated moderate. In 2017, 25% of the people stated that wheat production was poor, 70% stated that production was moderate, and 5% responded high production. In 2018, 60% of residents stated that wheat production was poor and 40% stated moderate production.

3.7 Climate Change Impact on Agriculture in Amarkantak

The irregularity in rainfall causes direct impact on forest and agricultural production. The low rainfall affects crops like rice, wheat, and maize production. Fishery is also affected due to low rainfall. The dams, rivers, and ponds are facing water stress. From the field survey, it was found that the lack of rainfall causes noticeable effect on the production of agricultural crops. Questionnaire was prepared, and overall people's response of crop production is shown in Fig. 3.3. From the field survey, it was found that the production of rice was also affected. In 2016, 61% of residents stated that production was poor, 23% stated that production was moderate, and 16% stated that production was good. In 2017, the rice production was moderate. 31% of residents stated that production was poor, 54% stated that production was moderate, and 15% responded good production. In 2018, the production of rice was not good for the farmers of Amarkantak area. 77% of residents stated that production was poor, 15% said production was moderate, and 8% stated that production was good. Figure 3.3b shows that in 2016, 77% of residents stated that production of maize was moderate, 8% said that production was poor, and 15% said that production was good. In 2017, 80% of residents responded that maize production was moderate, 15% of residents stated that maize production was poor, and 5% of residents stated that maize production was good. In 2018, 78% of the people stated that maize production was moderate, 16% of residents stated that production was poor, and 18% said that production was good. Figure 3.3c shows that in 2016, 46% of residents stated that production of wheat was poor, 23% of residents stated that production was moderate, and 21% of residents stated that the production of wheat was good. In 2017, 62% of the people stated that the production of wheat was poor, 8% of residents responded moderate production, and 30% stated production was good. Traditional food crops like kodo, kutki, etc. are now near to extinct. Production of kodo millets decreased to 75% from last the 4–5 years. *Paspalum scrobiculatum* (kodo) cultivation has decreased, and now it is not considered as

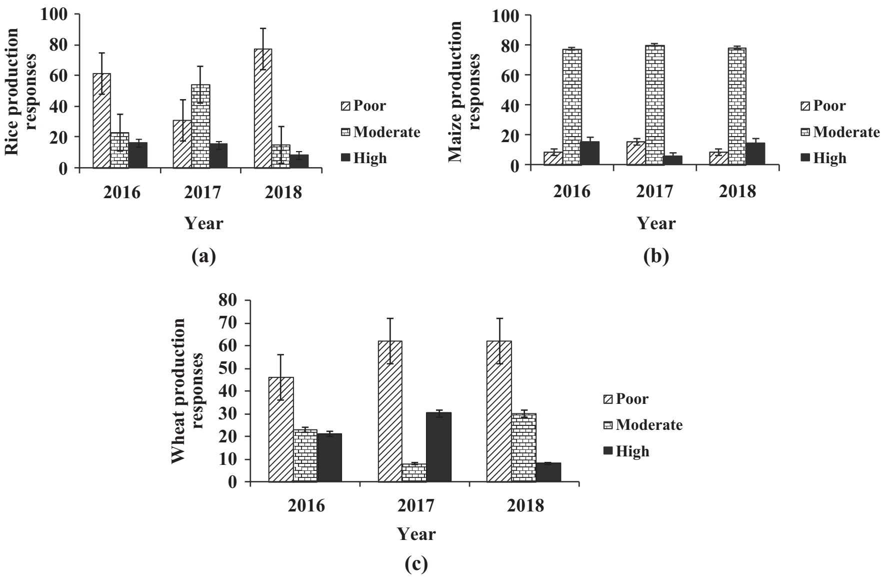

Fig. 3.3 (**a**) Rice production response (**b**) Maize production response (**c**) Wheat production response of Amarkantak area

main food crop. Freshwater fishery is now very difficult because of water stress in river, ponds, dams, and lakes. In the last few years, local people are suffering from lack of fish production in water bodies.

3.8 Impact on Forest and Forest Produces

The availability of non-timber forest products (NTFPs) has decreased in the forest of Amarkantak. According to forest dwellers, wild edible fruits like char (*Buchanania lanzan*), tendu (*Diospyros melanoxylon*), amla (*Phyllanthus emblica*), bel (*Aegle marmelos*), karonda (*Carissa spinarum*), and bhelwa (*semecarpus anacardium*) already decreased in production. Many medicinal plants are not available in forest due to forest fires and overexploitations. *Pterocarpus marsupium* (beeja) plants, famous medicinal plant, are found rarely in some parts of forest in Amarkantak. Water bodies are not having enough water from rainfall. Apart from average temperature of the area, water resources like, river, dam, and wells are increasingly becoming dry. The groundwater table of this region is likely to be decreased deep in the bore wells and hand pumps. Many water resources are now extinct, and some are now becoming seasonal.

3.9 Importance of Tendu Leaves (*Diospyros melanoxylon* Leaves) in Madhya Pradesh and Climate Change Impact

Tendu leaf is one of important minor forest products in Madhya Pradesh. The tribes and non-tribe communities living near the forests have economic benefit by collecting the tendu leaves. Madhya Pradesh is a leading state in India in the production of tendu leaves (*Diospyros melanoxylon* leaves). Tendu patta (*Diospyros melanoxylon* leaf) production data of the last 10 years in Anuppur district of Madhya Pradesh is shown in Table 3.2.

Table 3.2 Tendu patta (*Diospyros melanoxylon* leaf) production data of Anuppur district of Madhya Pradesh

Year	Rainfall (mm)	Weight (kg)
2009–2010	920	813,248
2010–2011	1073	834,012
2011–2012	1016	801,188
2012–2013	1518	107,303
2013–2014	1963	736,055
2014–2015	1721	661,655
2015–2016	1031	704,781
2016–2017	1139	784,144
2017–2018	1349	966,979
2018–2019	1210	729,692

Source: Divisional Forest Office Anuppur Madhya Pradesh

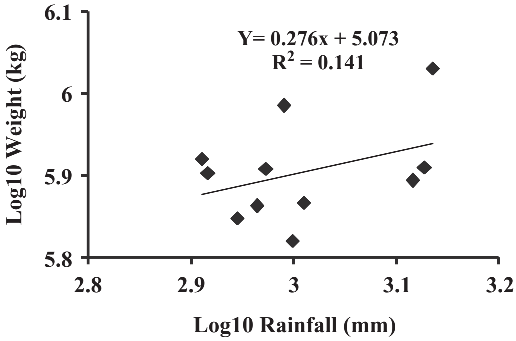

Fig. 3.4 Correlation between rainfall and tendu leaf production

The average annual production of tendu leaves in Madhya Pradesh is 25 lakh standard bags, which contributes 25% of the total production of India. One standard bag of tendu leaves in Madhya Pradesh means 1000 bundles of 50 leaves each. The tendu tree (*Diospyros melanoxylon*), belonging to family Ebenaceae, is endemic to Indian subcontinent. Tendu leaves have excellent characteristics of wrapping material. The major consumption of tendu leaves is in the beedi (local cigarette) industries. As a result, tendu leaves and beedi rolling have become an important source of income for the rural poor (Planning Commission 2011). According to B.N. Gupta, state of non-wood forest products in India, in the mid-1980s, annual production of tendu leaves was stable at around 300,000 metric tons (Lal 2011). A regional expert consultations on non-wood forest products at FAO Regional Office of Asia and Pacific, Bangkok, 5–8 November 1991 reported that tendu leaf production was grew to 450–500,000 mt in the 1990s and declined to 400,000 mt in 1999 (FAO 2005).

In the present study, the last 10 years of tendu leaf production data of Anuppur district has been collected from the Divisional Forest Office Anuppur. The tendu leaf production data were collected in standard bags which contains 1000 bundles in 1 standard bag and 1 bundle contain 50 tendu leaves. The standard bag quantity was converted into kilogram (1 standard bag = 40 kg) (Lal 2011). The correlation between the length and weight relation after Log10 transformation of rainfall and weight is shown in Fig. 3.4. It reveals that there is a definite positive correlation ($y = 0.276x + 5.073$), but the strength of the relation is weaker ($R^2 = 0.141$). Factors other than rainfall might affect the tendu leaf production like a market price, collector's motivation, and nearby availability.

3.10 Conclusion

Climate change has not only negative impacts but also positive impacts in the form of productivity and growth of plants and animals' species. Climate change has negative as well as partial positive impacts in forest and agrobiodiversity. From the survey, it was found that the quantity of rice production has decreased in the Amarkantak area. Apart from that, the quantity of maize, wheat, and soya bean production has also decreased in the sense of kilogram per hectare. The fishery activity has been greatly affected due to the lack of water in rivers and ponds. The forest resources have also decreased, and locals are not able to get enough quantity which can drive their livelihood. The forest fire in the Amarkantak region causes the extinction of few plants' species in the area. The medicinal plants of the region have declined in the forest. Low average rainfall and rising temperature affect the groundwater as well as surface water. Warm temperature potentially increases the evaporation rate and causes water stress for surface water bodies. The natural forest of Amarkantak is now in threats due low average rainfall and rising mean temperature. Degradation of forest and agricultural land can drive the climate change impact on the region which also affects the livelihood of the tribal. It is necessary to conserve the forest and biodiversity of the region to sustain the life of the local people. The livelihood options for the tribes of Amarkantak depend on agricultural and forest products. Climate change can disturb the livelihood option which is a challenging issue. The study of climate change impact on Amarkantak region will be helpful to understand the change of climatic conditions and its impact on biodiversity. The study will also be helpful to assess the impact of climate change in Amarkantak in the near future.

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Agricultural Sustainability and Climate Change Nexus

4

Deepika Pandey

Abstract

The phenomenon of climate change is affecting life on Earth in numerous ways, and agricultural sector is affected utmost as it is highly sensitive to the climatic factors. Agricultural sustainability is the call of the time when the growing population in the world needs to be nourished, while at the same time struggling with the effects of increasing pollution and deterioration of available agricultural land. As the resources obtainable on the earth are increasingly constrained, the stressed agricultural system has to survive and excel to be able to arrange for the basic human necessity of food. Water, energy and food systems are interconnected, and these systems must be linked to each other. However, the process is two-way round, wherein the climate is also distressed by the intensive practices applied to meet the increasing demand. This is the nexus of agricultural sustainability and climate change. The more one segment is stressed, the more the other segments are affected. A balance cannot be attained unless the complexity of the interconnections among the different sectors is understood and the challenge of adaptation is accepted, giving preference to the interdependence of the factors of the agricultural system.

Keywords

Sustainable agriculture · Climate change · Food security · Nexus

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4.1 Climate Change: A Reality

The variations in the temperature, humidity and precipitation of the atmosphere of a region over a long period of time are called climate. While weather is defined as the short-term changes in the atmospheric conditions, climate is the long-term exposition of the weather conditions of a specific area. Hence, when there is a gradual and steady change in the climate of an area, which is a result of changes in the average daily weather conditions over a long period, it is stated as climate change. The causes of climate change are by both natural and anthropogenic means. The weather is a set of meteorological conditions like wind, precipitation, snowfall, daylight, atmospheric temperature, humidity, pressure and so on at a specific place and time. However, the long-term summary of these weather conditions, considering their average values, is climate. The climate of a region decides the distribution of vegetation, type of ecosystems, animal and plant diversity, livelihoods and settlement of people in the region and their agricultural practices.

The variability in the climate is observed as periodic or erratic changes in the weather conditions, which can be related to El Nino or La Nina, volcanic eruptions or any changes in the dynamic system of the earth's processes. Climate variability also comprises the variations that occur from year to year and the incidences of extreme conditions like severe storms, unprecedented rainfall, unusually hot seasons or fluctuations in rainfall. It is observed by scientists from all over the world that global temperatures have risen remarkably fast over the past few decades (Bhattacharya 2019). The evidences for increase in the average global air and ocean temperatures, melting of ice and snow at permafrost regions and rising of average global sea levels are prevalent. According to the IPCC Fourth Assessment Report (2007), global warming is not an unassuming speculation, but very much evident and ongoing. The average temperatures of the atmosphere and the ocean, during the past five centuries, are at an all-time high, and this trend has been dominant for more than a millennium now.

It has long been confirmed by scientists that some gases present in the atmosphere act as a blanket that blocks the sun's rays reflected from the earth's surface from escaping to the outer atmosphere, and hence the Earth's surface stays warmer than it would have without these gases. These gases have the effect of a greenhouse (horticultural glass house) and are known as greenhouse gases (GHGs). Their increased concentration in the atmosphere would result in an enhanced greenhouse effect and can cause additional warming of the Earth's atmosphere. The greenhouse effect is caused by gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorocarbons (PFCs, HFCs) and so on present in the atmosphere. An enhanced greenhouse effect, better known as global warming, is caused by an increase in the concentration of these GHGs. The Industrial Revolution in the eighteenth and nineteenth centuries was accompanied by excessive fossil fuel consumption and a rapid increase in the concentration of CO_2 in the atmosphere. It was in the 1970s when information on warming of the atmosphere and increased concentration of greenhouse gases was attained from many parts of the world that the issue of warming of atmosphere attracted international scientists and the acknowledgement of anthropogenic greenhouse gas emissions as the cause of global warming became well known. The major greenhouse gas to be effective in causing global warming was recognized as carbon dioxide. The concentration of carbon dioxide before the Industrial Revolution was estimated to be 280 ppm in 1750; however, by 2005, the concentration of carbon dioxide reached 379 ppm, further increasing to 400 ppm in 2013 (ESRL, NOAA). Examination of the average temperatures shows that the rate of increase of the average temperature of the Earth since the Industrial Revolution has been much more than the increase before the Industrial Revolution. To be precise, global warming has significantly intensified since 1980. If we observe the average increasing trend in CO_2 concentration before the 1970s, it was 0.73 ppm per year, which increased to 2.11 ppm per year after 2005. The Earth's temperature has increased at the rate of 0.7–0.9 °C for every century till 1901, but this rate almost doubled from 1975 at 1.5–1.8 °C, as per the international report (State of the Climate 2017).

The phenomenon of global warming was evident through the increase in the temperature of the North and South Poles, ice cap melting at an increased rate and reduction in the ice-breaking period in the polar lakes, leading to a substantial rise in the sea level. Extreme climatic phenomena such as flood, drought and heat waves along with increased occurrence of natural disasters worldwide are also associated with global warming. The consequences of climate change are not limited to warming of the atmosphere but also affect the hydrology, including underground water level, water temperature, river flow and water quality of lakes and marshes. The warming of the atmosphere has an impact on precipitation, evaporation and soil moisture content. The change in the precipitation pattern as a result of climate change particularly increases the precipitation and hence the outflow, while the temperature rise increases evaporation, resulting in outflow reduction. This directly affects the flow of the rivers and availability of underground water. The variations in seasonal precipitation as well as temperature changes can also be a consequence of climate change. The climate change consequences visible in the form of melting of the ice on the poles, causing glacial regression, permafrost thawing, flooding as well as drought in the rivers and lakes, erosion of coastal regions, sea level rise and extreme phenomena in nature affect not only the physical but the biological systems of the planet. The biological systems are affected directly or indirectly as a consequence of other climate change-related phenomena like wildfires, fauna and flora displacements and even the death of sensitive species of flora and fauna due to extreme weather conditions. Crops and food production are largely affected by diseases and even death due to rise in the ambient temperature.

Changes in the patterns of precipitation and temperature systems of the atmosphere have pronounced effects on crop production and are being reported from all over the world. Especially in the developing world, where the economy is based on agriculture, the unprecedented change in the climate is disturbing the economic as well as the social sector. The tropical regions and the underdeveloped countries of this region are the worst affected. Several studies have reaffirmed that increased precipitation enhances the agricultural productivity but increased temperatures are having a negative effect on the agricultural yield. This reality has been experienced in almost all parts of the world perceptively or unintentionally. Agriculturists all over the world experiencing these effects are finding ways to mitigate them. The long-term scarcity of water and other resources, deteriorating soil conditions, outbreak of diseases in crops and livestock, increase in the occurrence and intensity of drought and floods, desertification and so on, due to warming of the atmosphere, are already causing an alarming situation. The agricultural yield is highly dependent on the actual climate set-up experienced at the local level and the damages due to climate change are real. The already dry regions are expected to bear further losses but the cooler regions may be expected to increase their production in warmer conditions.

4.2 Pressure on Agriculture

The increasing population of the world has put a huge challenge on the agricultural sector of the world to be able to feed all and provide proper nutrition. Millions of people in various parts of the world still face food insecurity and suffer from hunger. The future and development of any country is influenced by the health of its young generation, but malnourished newborn children have posed a serious threat to the development and security of a substantial part of the world. The Global Nutrition Report, in its latest edition released in November 2018, reveals that the global problem of malnutrition is excessively high and every country in the world is affected. Increased agricultural productivity is the only answer to this problem, to be able to produce sufficient food for the surviving population.

Agricultural production needs to exhibit a substantial increase by 2050 in order to be able to provide food to the ever-growing and urbanized population. Approximations about the growth in agricultural yield ranges from 25% to 70%, taking into account the assumptions made about agricultural efficiency and changes in the pattern of consumption (Alexandratos and Bruinsma 2012; Mitchell et al. 2017). Food may be available, but nutrition is lacking. The number of undernourished people in the world reached 925 million (FAO 2010) in 2010. To meet this growing demand for food production with increasing population that is predicted to exceed 9 billion in 2050, the global food production must increase by 70% in the first 50 years of this century (FAO 2009). A study on 141 countries of the world reveals that 124 countries (88%) experience more than one kind of malnutrition, with 41 countries (29%) having high levels of all forms of nutrition: anaemia, overweight and stunting (Global Nutrition Report 2018).

Already under pressure of increasing food production, any factor that affects the yield of agriculture becomes a serious threat for mankind. In light of the foothold of climate change, the local and global changes in the weather conditions are expected to become more recurrent and severe, in addition to the long-term change in climate, with more recurrent and devastating extreme events (IPCC 2013). These changes in the weather conditions, sometimes reaching extremes, are being experienced in various parts of the world and pose a serious challenge for agriculture to meet the food and nutrition demand of the ever-increasing population of the world (Rotter et al. 2019).

To meet the growing demand for food, the agricultural sector has adopted several intensification techniques and the industrialization of crop system in most countries which thrive to achieve the goal of self-sufficiency in food production as well as feed the less privileged people of the world. The ways adopted (Scherr and McNeely 2008) to increase the output per hectare in various countries are (1) increase in agricultural area, (2) use of genetically modified crops, (3) crop rotation, (4) extensive irrigation and (5) rigorous monoculture. High-technology farms are adopting the pathway of minimized labour inputs and maximized technology-based inputs. Use of excessive fertilizers, artificial culture production and availability of enough water for irrigation have caused an increase in the growing period and successive crop production without fallow period. However, in spite of the technological advancement and extensive approach to increase the farm land productivity, it is a fact that the growth of agricultural yield has been dropping. It has been reported that the average annual growth rate of cereal production has reduced from about 2–3% in the 1970s and 1980s to 1–2% in the recent decade (World Bank 2006). This has been attributed to climate change, and it is expected that a drop of 9–21% in the overall agricultural productivity may be experienced by developing countries as an effect of global warming (FAO 2009). As a result, the goal of feeding all the people of the world may remain unfulfilled.

In India the food security achieved through the Green Revolution may be at risk once again due to continuous population growth. It is estimated that the population of India will grow to 1.6 billion by 2050. This continuous increase in the population will imply a greater demand for rice and wheat, which are the predominant staple foods. A similar increase in demand is also expected for pulses, fruits, vegetables and dairy and marine products. The additional demand for food will have to be met through the same land available for cultivation, and probably this will also shrink due to stress and deterioration. The average yields of rice, wheat, coarse grains and pulses are required to rise by 56%, 62%, 36% and 116%, respectively, by 2020 to meet the demands of the growing population. Amidst the pressure to increase crop production to meet higher food demands, reports of a significant slowdown of the growth rate in production and yield from the cultivated areas have become common. The annual rate of growth in food production and yield, which peaked during the early years of the Green Revolution, is showing a decline since the 1980s.

4.3 Climatic Factors Affecting Agriculture

The growth and development of plants are influenced by climatic factors such as availability of water, light and changes in temperature, relative humidity, air and wind. These are abiotic components of the environment, which also include topography and soil.

4.3.1 Rainfall

Rainfall being the most common form of precipitation is the basic requirement of crops and it influences the crop production throughout the world (Eagleman 1985; Miller 2001). It is vital for the crop growth and yield to get a regular and sufficient amount of rainfall.

The variation in precipitation and climate affects the selection and dominance of vegetation type and determines the crop production. The amount of rainfall received and its frequency are directly influenced by the increase or decrease in the temperature of the atmosphere as the formation of high and low atmospheric pressures and their duration decide the movement of air. Ill-timed rainfall may cause excessive flooding or scarcity of water and cause a huge reduction in crop production. Increased evaporation due to high temperatures may increase the demand for water required for crop production. This drought and flood cycle due to unprecedented rainfall is a nightmare for farmers growing rain-fed crops. The precipitation in the form of freezing rain, snowfall, hail and ice pellets may have devastating effects on crops if they are untimely.

4.3.2 Light

Light is essentially required by plants right from the germination of seeds to the maturity of fruits; this climatic factor is essential for the production of chlorophyll and also indispensable for photosynthesis. Light also plays an important role in stomata movement and phototropism and causes enhancement or inhibition in processes such as translocation, mineral absorption and abscission (Devlin 1975; Poincelot 1980). The properties of light that affect plant growth and development are the light quality, intensity and day-length or photoperiod. The specific wavelengths of light are light quality, the degree of brightness that a plant receives is the light intensity, and day-length is the duration of the day with respect to the night period. Change in this climatic factor affects flowering, seed production and seed maturation of the plants. Hence, it is an important factor for determining crop production.

4.3.3 Temperature

As we know, the degree of hotness or coldness of a substance is called temperature (Eagleman 1985). It is commonly expressed in degree Celsius or centigrade (C) and degree Fahrenheit (F). It is an important factor influencing the growth of plants as the enzymatic activities for the growth and maturity of plants, flowering, fruit bearing and so on are directly affected by changes in the diurnal temperature. The process of photosynthesis is reliant on incoming radiation and can be modified by changes in the temperature of the atmosphere and rainfall.

The temperature mainly controls the duration of the growth period and also affects expansion of leaf area, respiration and evapotranspiration. Hence, all the processes associated with dry matter accumulation in plants are directly or indirectly linked with temperature. The enzymatic activity and rate of chemical reactions tend to increase with the increase in temperature. There is doubling of the enzyme activity with every 10 °C rise in temperature (Mader 1993), but a further increase in temperature denatures proteins and enzymes and inhibits growth, and may also cause death of sensitive species. Extremely low temperatures also cause limiting effects on plant growth and development. At low temperatures, the water in the soil becomes more viscous and less mobile, and protoplasm is less permeable; this affects the absorption of water by plant roots. However, below the freezing point water solidifies in soil as well as in living cells and may rupture the cell walls (Devlin 1975). As temperature has an impact on breaking of seed dormancy, seed germination, protein synthesis, and translocation, there is an optimal temperature range for plant growth, maturity, flowering and bearing fruits. The translocation of photosynthate is faster at higher temperatures and causes the early maturity of plants. The favourable day-and-night temperature range for plant growth differs from species to species and, hence, the maximum yield of the crops also varies with changes in the temperature of the atmosphere.

4.3.4 Air

Air provides one of the basic raw materials for the process of photosynthesis, carbon dioxide, which is crucial for the growth of plants. Besides CO_2, the clean air is a mixture of gases, with 78% nitrogen, 21% oxygen and a slightly less than 1% of argon. Carbon dioxide, at a little higher than 0.036%, and traces of other gases are also present in the current atmospheric composition. 75% of the air is present in the lowest layer of the atmosphere called the troposphere (Miller 2001), which is closest to the Earth's surface. Oxygen is essential for respiration for both plants and animals. It is required by plants for the production of energy for various development processes. Nitrogen, an essential nutrient, is also utilized from the atmosphere by nitrogen fixing bacteria in the leguminous plants as well as free living bacteria in soil.

As carbon dioxide is a necessary ingredient for photosynthesis, the increasing concentration of carbon dioxide in the present scenario gives a positive feedback in terms of increasing crop yield. The C3 plants, which are the major source of cereals of the world, are found to respond positively with the increased concentration of carbon dioxide. The difference between C3 and C4 plants are in their biochemical mechanisms to fix CO_2 and make carbohydrates through photosynthesis. In C3 plants, CO_2 is taken directly from the air during photosynthesis for production of glucose, whereas in C4 plants CO_2 is concentrated inside the plant to produce malate (an organic compound), which then enters the photosynthesis cycle. Thus, C3 plants respond directly to increased CO_2 levels in the atmosphere and show increase in the crop yield. However, C4 plants may not be affected much by the increased carbon dioxide concentration in the atmosphere.

4.3.5 Relative Humidity

The relative humidity is the amount of water vapour present in air. It is defined as the proportion of water vapour present in air to the maximum amount of water vapour the air can hold at a certain temperature. A relative humidity of 60% at 27 °C temperature signifies that every kilogram of the air holds 60% of the maximum amount of water that can be detained at that temperature. The growth of plants is affected by this physiological factor in a significant way, as the stomata opening and closure, which controls water loss through transpiration and photosynthesis, is affected by relative humidity. Relative humidity is also indirectly affected by atmospheric temperature, wherein warmer air has the capacity to grasp more water than cold air.

4.3.6 Wind

Moving air or wind helps in the process of pollination of flowers, which is crucial for fruit formation and seed development. Wind plays an important role in grasses for seed development because they possess wind-pollinated flowers. As the grain production of the world comes from the grass family, wind becomes an important factor for grain production. The pressure gradient is caused by heating of the Earth at the local and global scales, and this gives rise to the movement of air or wind. When the air cools down, it contracts and increases the pressure; however, it expands when it warms, and the pressure goes down. Cold air flows from high pressure to low pressure to balance the difference in the pressure. Wind affects the exchange of gases through stomata, but if the wind is strong, there is excessive water loss through transpiration, and it can also cause lodging or falling of plants. When the rate of water absorption by plants is less than the rate of transpiration, the stomata are closed partially or even completely. This restricts the diffusion of carbon dioxide into the leaves, and can affect the rate of photosynthesis and overall growth of plants, which has a direct consequence on crop yield (Edmond et al. 1978).

The above-discussed climatic factors may independently produce a limiting effect on the various growth processes of plants; however, these climatic factors do not operate in isolation and are found to have interactions with each other and influence each other under natural conditions. Agricultural sustainability is highly influenced by climate change as it involves all the factors that directly affect the productivity of crops. The low cereal production on the British Isles and in the Alpine countries is because of less availability of solar radiation, which becomes the limiting factor and causes yield and quality losses. The cold and rainy summers in these regions reduce the productivity period. In the Mediterranean countries, the situation is just the opposite: the limiting factor here is the water availability and heat stress. The restricted rainfall in this region needs to be compensated by adequate irrigation facilities to keep up with food production. The low production of cereals in these areas is overcome by choosing permanent crops such as olive, grapevine and fruit trees as more important food by the local people over cereals.

4.4 Need for Agricultural Sustainability

On account of the challenges posed on the environment, due to decades of industrialization and development, sustainability is the only response to come to terms with the current scenario and find a dependable future for the survival of life on Earth. Sustainable Development Goals of the millennium features ending the hunger of people and providing good health and well-being as the top goals. The agricultural sector bears a huge responsibility for adopting a sustainable way and fulfilling the basic need of providing food to all.

The common modifications to achieve technological advancement in farming include rapid technological innovation, large capital investments to introduce advance production and management technology, large-scale farms, single crops grown continuously over many seasons, high-yield hybrid variety of crops, extensive use of pesticides and fertilizers, external energy inputs and high labour efficiency. The conventional farming systems were modified from farm to farm and from country to country to meet the growing need. In the case of livestock, the highly demanded production comes from confined and concentrated systems. The adoption of extensive agricultural techniques has affected the agricultural sector positively by increasing the yield and has reduced many risks in farming. The increased crop production from the limited land available may have met the increasing food demand in many situations; however, they have come at a significant price. The ill-effects of extensive agriculture are exhibited in the form of depletion of plant micronutrients in the topsoil, contamination of ground and surface water due to pesticides and fertilizers, pollution of air, greenhouse gas emissions, spread of new pathogens, carelessness in maintaining working conditions of farm labourers, new fears to human health and safety due to introduction of genetically modified varieties, decline in farms owned by families, economic attitude in food and agricultural production, and fragmentation of rural communities.

The unregulated use of pesticides in the 1960s, which resulted in the severe decline of the bird population as pointed out by Rachael Carson, was a direct effect of the one-sided approach of humans to attain the maximum yield without having any consideration for the environment and their fellow living beings. Other challenges of agricultural amplification as proved by several researches, were in the areas of ecosystem services such as the natural health of the soils and agents of pollination (Kleijn and Sutherland 2003; Kremen and Miles 2012; Pimentel and Pimentel 2007). The pressure on agriculture to increase the food production in times of climate change and increased climate variability needs to be addressed keeping in mind the improvement of the nutritional value of the crop, reduction in greenhouse gas emissions and the carbon cost of farming (Tubiello et al. 2015). However, due to less availability of land for agriculture, this goal cannot be achieved by simply converting other fertile lands for crop production, which cannot be economically or environmentally accepted (Keating et al. 2014; Searchinger et al. 2015).

Scientists have come up with several responses to these needs and some among them are introduction of sustainable intensification (SI) approach (Garnett et al. 2013; Montpellier Panel 2013) and climate-smart agriculture (CSA) (Thornton et al. 2018; Lipper et al. 2014). The farming system that is accomplished for maintaining the productivity of the soil and the long-term usefulness to society is appropriate to be defined as sustainable agriculture. Sustainable agriculture must be resource-conserving, environmentally sound, economically beneficial, socially supportive and commercially competitive. Several authors have described agricultural sustainability as an idea comprising the environmental, economic and social aspects of agriculture and also validating the resilience of farmlands to remain productive all the time (Ikerd 2005; Garibaldi et al. 2016). The answer to finding the sustainable way of agriculture lies in looking towards the traditional agricultural practices which are based on minimum tillage, mulching with crop residue after each season of cropping and rotation of crops. These practices naturally increase the yield of crop production by improving the fertility of soil naturally and decreasing the risk of standing crop destruction from unpredictable rainfall (Brouder and Gomez-Macpherson 2014) and the retaining water which may get lost due to the impact of climate change (Wagena and Easton 2018). These conservative agricultural practices increase the soil carbon, hence enhance the yield resilience and at the same time have a positive effect on the environment (Lal and Stewart 2010). If agriculture is practiced by management and utilization of the ecosystem in such a manner that the productivity, regeneration capacity, vitality and biodiversity of the system are maintained, then the system may function with equal capacity and productivity in the future as it is functioning today. The sustainable agro-ecosystem should also not be harmful to other ecosystems. As mentioned earlier, sustainability is achieved by the ecological, economic and social footprints functioning at the local, national and global levels. However, environmental sustainability in agriculture refers to the maintenance of land and plant resources and their natural systems in the good stewardship that the agricultural system depends upon. Among other things, this involves building and maintaining healthy soil, managing water wisely, minimizing air, water and soil pollution and promoting biodiversity.

4.5 Effect of Climate Change on Agriculture

4.5.1 Major Impacts

Hydrologic: The precipitation cycle has changed, and the frequency and intensity of droughts and floods have increased in many regions practising agriculture. Such events are highly damaging for crops.

Heat The average temperatures are expected to increase at least by 1.0 °C over the next 30–50 years. The regional changes are anticipated to increase in the number of heat waves and warm nights, decrease in the number of frost days and a longer growing season in temperate zones. In the tropics, increased temperatures may increase productivity but will be balanced by increased extreme events.

Carbon Dioxide The atmospheric carbon dioxide (CO_2) concentration has increased to about 450 ppm and is expected to increase even more in the next 20–30 years. The C3 species (wheat, rice and soybeans), which account for more than 95% of the world's grain species, respond with an increased yield with increased CO_2 concentration, compared to the C4 species (corn and sorghum). However, C3 weeds have also responded well to elevated CO_2 levels, showing the possibility of increased weed pressure and reduced crop yields.

Crop Biodiversity The wild crop varieties, an important genetic resource indispensable for crop breeding, will be severely affected due to fluctuating weather conditions and extreme events.

Economic Consequences Reduced production and increased demands will cause a rise in prices for the most common and chief agricultural crops such as rice, wheat, maize and soybeans. This will also increase the price of animal feed and will further affect the meat prices. Climate change will therefore tend to slightly reduce meat consumption and cause higher a reduction in cereals consumption, which will lead to greater food insecurity.

The climatic factors that are essential for crop development and productivity pose a threat of declining yield if they change by natural or anthropogenic causes (Rosenwelg and Parry 1994). Agricultural productivity is mostly determined by the temperature of the atmosphere, availability of water and nutrients and incoming solar radiation. As agriculture is highly exposed to climatic conditions and its activities are dependent on the climate, the uncertainty of climate increases the threat of low farm yield and high risk to farmers. It is difficult for farmers to decide the appropriate time for sowing, ploughing, selecting crop and investment of time, land and money under climate uncertainty. The global hydrological cycle is directly influenced by climate change, and as a result, the precipitation is intensified and unpredictable (Trenberth 2011). As the atmosphere becomes warmer, the rate of evaporation of water will increase and there will be increased amount of water vapour in the atmosphere, leading to greater precipitation intensity. This is how the risk of extreme precipitation and flooding is increased (Kundzewicz et al. 2014; Wasko and Sharma 2017). Warming of the atmosphere is bringing a threat to the availability of water for irrigation and increases the crop water demand (Elsner et al. 2010). The effect of climate change varies from crop to crop and from country to country (Adams et al. 1998). The colder countries benefit from a rising temperature, to be more favourable for crop growth (Stokes and Howden 2010), while warmer countries of the semi-arid region suffer due to increased water stress and reduced crop yields.

However, a combination of these impacts may have either positive or negative effects depending upon the other factors functioning in a country. The agricultural vulnerabilities are aggravated by the extremities brought about by climate change

(Füssel 2007). The reduction in food production due to climate change has already been reported from various regions of the world (Lobell et al. 2010). Small holding farmers are the worst affected, particularly in under-developed countries in sub-Saharan Africa (Mendelsohn and Dinar 1999; Schlenker and Lobell 2010; Wheeler and von Braun 2013). In a country like India, the effects of increased temperature, water stress, changes in precipitation pattern or reduction in number of rainy days have already affected the wheat and paddy yield. The yield is expected to reduce by 4.5–9% in 2020–2039 under the present climate change situation (Sahoo et al. 2013). Climate change not only impacts the rural economic set-up of the farmers and their society by affecting agricultural productivity, household revenues of the farmers and their asset values, it also brings infrastructural changes in agriculture by impacting the availability of water resources for agriculture.

The complex effect of global warming has different effects on different types of crops, and their response is also varied depending on their adaptability. In the tropics, the main occupation of about two-thirds of the population is agriculture, and 75% of the world's population lives in the tropics. These tropical regions are also the ones that are under-developed and are not exposed to technological advancement. This agriculture-based population is exposed to a wide range of pests, plant diseases and weeds, land deterioration and pollution, economically vulnerable rural society, inadequate land distribution and rapid population growth. Hence, any influence on the tropical agriculture sector will affect the livelihood of a large number of people.

Adopting supplemental irrigation rights may be one way to make irrigation-dependent farmers more resilient during water scarcity due to climate change (Bigelow and Zhang 2018). The probable positive effects of global warming can be increased crop production due to enhanced carbon dioxide concentration in the atmosphere, increased area for production of tropical and sub-tropical crops, increased cultivation and hence expansion of two-crop farming, reduction in crop damage in winter crops due to low temperature and reduction in the heating cost of the agricultural crops grown in cold areas. However, the increased global temperature will have negative impacts on agriculture in the form of crop quality, reduced shelf-life of fruits and vegetables, increase in disease outbreak, increase in weeds, reduction in fertility of land due to increased rate of decomposition, blights, harmful insects, increased soil erosion due to increase in intensity and frequency of rainfall, etc.

The shifting climatic conditions may change the areas under farming, making main areas less productive and bringing unsuitable areas under suitable growing conditions. Hence, a crisis for one place may become an opportunity for the other, having an overall neutral effect. This depends upon the adaptation strategies by countries to combat climate change, which can maximize the opportunities and develop a sustainable agricultural system in the period of rapid climate variations. Crop damages may increase if the unforeseen climate change increases the climate variability. Its impact on agriculture will be one of the foremost key factors disturbing the future food security of mankind on the Earth. Understanding the weather changes over a period of time, predicting the change in weather and adjusting the management practices accordingly to achieve better harvest are challenges to the progress of the agricultural sector as a whole. The climate dependability and sensitivity of agriculture remains uncertain to a great extent, as there is regional variation of the climatic factors as a consequence, such as rainfall and temperature, which influences crops and harvesting systems, soils and management practices. In tropical countries, this dependency is more pronounced and the production of grains and other crops is affected by season, timing and amount of rainfall.

4.5.2 Climate Change Impacts on Indian Agriculture

India is one of the most affected countries, as the monsoon plays a very important role in defining crop production, and hence any change or delay in the monsoon has a drastic effect on crop yield, and the farmers have to bear the cost. The monsoon rainfall all over India does not show any significant trend as a consequence of climate change; regional climatic variations during the monsoon have been observed (Mall et al.2007). Along the west coast of the country, an increase in monsoon seasonal rainfall has been observed in northern Andhra Pradesh and north-western India, whereas a decreasing trend in monsoon seasonal rainfall has been observed over eastern Madhya Pradesh, north-eastern India and some parts of Gujarat and Kerala. In India, the coastal regions are facing an increasing trend in severe storm incidences. West Bengal and Gujarat have reported increase in the frequency of extreme weather conditions, whereas in Odisha a drop has been observed. An analysis of everyday rainfall data has shown a rise in the frequency of heavy rainfall and a significant reduction in the frequency of moderate rain events in the central part of India from 1951 to 2000. Sea level rise affects the coastal regions and islands the most. They lose a lot of productive land under water in such conditions. Climate change may bring more land under water and will result in loss of fertile agricultural lands and huge losses in agricultural produce. Scientists have estimated that elevation in sea level in the north Indian Ocean is observed to be between 1.06 and 1.75 mm per year, and these rates are consistent with 1–2 mm per year global sea level rise as estimated by the IPCC. The same analysis has projected that the intensity of the Indian Summer Monsoon (ISM) will increase in the early period of 2040 and by 10% by 2100. Estimates of Climate Change Modelling in India and other studies on increased atmospheric GHG concentrations arising from increased global anthropogenic emissions have projected that the annual mean surface temperature is likely to rise from 3 to 5 °C by the end of the century, with warming more noticeable in the northern parts of India. Changes in climate variables such as temperature, precipitation and humidity may have significant long-term implications for the quality and quantity of water availability. The major river systems, such as the Brahmaputra, Ganga and Indus, are expected to be particularly affected by the reduction in snow cover. A total flow for all river basins, except Narmada and Tapti, is expected to decline. On the other hand, the fresh water sources near the coastline will undergo salt intrusion due to sea level rise.

Studies on the effect of climate change on Indian agriculture indicate great losses especially in Rabi crop. Indian agriculture is sensitive to climate changes such as variability in monsoon rainfall and temperature changes within a season which affects the food production directly. With every 1 °C increase in temperature, wheat production is reduced by 4–5 Mt. According to IPCC reports, rice and wheat yield could significantly decline due to changes in climatic variables. Most of the precipitation in India comes through the southwest monsoon and it is critical for the accessibility of drinking water and irrigation. Indian agriculture is also sensitive to indirect effects through changes in soil moisture and timing and distribution of plant diseases and pests. More prominent effects of climate change are exhibited on cash crops, such as tea coffee, aromatic and medicinal plants, which are more sensitive towards change in temperature or precipitation. The quality of fruits, vegetables and basmati rice is also significantly affected by small changes in climatic conditions. The change in climatic conditions also modifies the population dynamics of pathogens and insects as their life cycles are highly affected by changes in ambient temperature and humidity. Agriculture-related sectors such as dairy and poultry are also affected by climate change, which may cause lower yields of milk and eggs and degeneration in fish breeding, migration and harvests.

A damage of 10–40% in crop production by 2011 is described in several global reports. As we have seen that the functioning of crop plants is highly susceptible to climate change and results in overall decline in yield, but also the socio-economic systems affected by floods, droughts, extreme weather events or untimely precipitation due to climate change have a considerable influence on the crop production. The ability of the affected society to deal with and the adaptability of farmers are key elements to minimize the effects. However, in India, due to the lack of balancing efforts and an established support system, farmers rely heavily on the natural factors. Hence, for every 2–3.5 °C rise in temperature, the loss in net revenue at the farm level is assessed to range between 9% and 25%. It has also been estimated that a 2 °C rise in the mean temperature due to global warming and a 7% increase in mean precipitation is likely to lessen net revenues for the country by 12.3% as a whole. The most severely affected states in crop production are the coastal regions of Gujarat, Maharashtra and Karnataka. However, Punjab, Haryana and western Uttar Pradesh are showing small losses, whereas West Bengal, Odisha and Andhra Pradesh are expected to be at an advantage to a small extent from warming.

An enormous increase in food production in India from 50 Mt in 1951 to 212 Mt in 2002 is attributed to the Green Revolution, which has amplified the mean cereal productivity from 500 to almost 1800 kg/ha. The vast increase in food production in the Green Revolution was largely due to area expansion, cultivation of high yielding semi-dwarf varieties on a large scale, availability and application of irrigation throughout the growing season, surplus use of fertilizers and biocides, and support by progressive government policies. This growth in agricultural production had enabled the government to maintain sufficient food stock for the food requirement of the population, as well as surplus for storage. However, a gradual increase in environmental degradation was perceived in the areas benefited largely by the Green Revolution. Deterioration of soil quality, decreasing water table, increasing salinity of the soil, resistance pests and dreadful conditions of irrigation water quality are the causes of concern in north-western India.

Slow removal of nutrients by crops over a long period of time has exceeded its application and hence farmers now have to apply more fertilizers to realize the same yield as achieved 20–30 years ago. The problems arising because of over-irrigation due to introduction of canal irrigation in Haryana has resulted in almost 0.5 Mha being affected by soil salinity. The water table in some canal irrigated districts has risen, increasing the complications of salinity. Irrigation with tube wells has resulted in over-exploitation of groundwater, resulting in declining water tables. Atmospheric warming imposed evaporative loss of water and reduction in the amount of return flow is an extra hazard to availability of water for irrigation (Malek et al. 2017). The tendency of increased plant pathogens and insect pests has become common under intensive farming systems such as the rice and wheat systems.

4.6 Role of Agriculture in Climate Change

Scientific studies have shown that over the past 50 years, the increase in agricultural production due to augmented areas under agriculture, mechanistic approach and intensive agricultural practices to meet the food demand of the growing population have resulted in a near doubling of GHG emissions from the agricultural sector, including forestry and fisheries (Rotter et al. 2019). It has been predicted that to feed the current global population with recent dietary patterns, the overall food production is required to increase by 70%, which may result in an additional 30% increase in global GHG emissions from the agricultural sector (Tubiello et al. 2015). Agricultural practices add to global warming by causing GHG emissions through various practices such as emission of nitrous oxide from soils, excessive application of fertilizers and pesticides, waste generated from grazing animals and methane production by gut of ruminant animals. The activities related to farming practices such as land-use changes, including land clearing and deforestation, further add to GHG emissions (Tilman et al. 2002). The excessive and improper use of fertilizers and pesticides in the crop field and non-judicial use of irrigation water and other agricultural machinery have led to an intensive form of agriculture which has harmed the environment considerably (Tilman et al. 2002; Pretty et al. 2003; Gliessman 2007; Srivastava et al. 2016).

Murad et al. (2010) have shown that the correlation of agricultural growth rate is weakly associated with climate change in a negative way, although a strong significant positive correlation was found between per capita carbon dioxide emission and agricultural production index, which points towards agriculture as a contributor of carbon dioxide. Carbon dioxide in agriculture is largely released from microbial decomposition or burning of plant litter and soil organic matter. Methane is largely produced from the gut of ruminant livestock as a result of fermentative digestion by ruminant bacteria or by rice grown under flooded conditions. It can also be released by store manures; it happens when organic materials decay under anoxic conditions. Another GHG, nitrous oxide (N_2O), is produced by the microbial conversions of available nitrogen (N) in soils and manures, where the available N is higher than plant requirements, especially under damp conditions. N_2O has 300 times more greenhouse potential than CO_2 and has long-term warming effects because of its 100-year residence time in the atmosphere (Suddick et al. 2013), which makes it one of the potential causes of global warming if released in high quantities. The major source for N_2O was found to be fertilized agricultural soils and livestock manure. In the United States, about 0.48 Mt of N_2O-N per year was produced from the agricultural sector, which is about 80% of the total anthropogenic N_2O production.

The contribution of the agricultural sector in total GHGs emission amount to be 5% and agricultural soil is the primary source of nitrous oxides (NRE 2015). Deforestation, livestock emissions, use of fossil fuel-based fertilizers, mechanized agricultural equipment and burning of biomass are other major contributors of GHGs in the agricultural sector. The United Nations Food and Agriculture Organization has shown that GHG emissions from agricultural sectors accounted for 21% of the total global emissions and were the second largest emitters. However, it is also stated in the report that the agricultural sector is capable of substantially reducing the total emissions by 20–60% in 2030. However, agricultural greenhouse gas (GHG) release mechanisms are various and heterogeneous, but the potential for mitigation is there through dynamic and accurate management of agricultural systems (Smith et al. 2008; Smith and Olesen 2010). The global carbon balance can be maintained by reducing deforestation, maintaining forested areas, reinforcement of management practices for plant and livestock, and generating and using renewable energy. In 2013, the BRICS (Brazil, Russia, India, China, and South Africa) countries, representing half of the global population and economic development, emitted more than 40% of the global total CO2 emissions (Liu et al. 2017).

4.7 The Nexus

Agriculture and climate are interconnected with each other at several levels and comprise a coherent system, which is called a nexus. Nexus is defined as the interconnections between different segments and the connections are bidirectional. Here for example, climate has a direct bearing on agriculture and subsequently impacts on agricultural yield, and agriculture, in turn, could have a direct effect on climate as well. The greenhouse gas emissions from waterlogged agricultural fields, guts of cattle reared on farms, imbalances in the nitrogen budget of the earth due to large-scale production of nitrates, use of various chemicals and so on have considerable effects on the climate. The concept of Nexus accepts that exerting on one part of the Nexus will create pressure on the other part. A Nexus comprehensible analysis is essential and can lead to the management and planning of resilient natural systems and designing of infrastructures.

Although the concept of Nexus is a relatively new idea (Hoff 2011), it has already fascinated researchers worldwide and caught their attention (Endo et al. 2017). This concept was defined by the UNFAO (FAO 2014; Brouwer et al. 2018), through the 'water–energy–food nexus'. It is a useful concept to address the complexity and interrelationship of our resource system at the global level, and we depend on them to achieve environmental, social and economic goals. For agriculture and the climate system, it is all about balancing of different resource user objectives and interests and maintaining the integrity of ecosystems along with that. According to Allan (2003), the nexus emphasizes on promoting the cooperation with various sectors and bringing in the opportunities for disciplinary divides. The increasing demand of food water and energy is a demanding challenge posed before unindustrialized countries and it is further aggravated by climate change.

Efficient use of vital resources, which include land, water and energy, is required by developing technologies to adapt to changes and organized efforts to reduce compromises and maximize collaborations. The policy process in South Asia, as in many Asian countries, most commonly follows an approach in which the mentioned sectors—water, energy and food—are not interconnected and operate independent of each other. This kind of strategy can increase the weakness of the system and decrease the capacity of one sector while increasing the vulnerabilities in another sector, resulting in unsuccessful adaptation and jeopardy of the system (Barnett and O'Neill 2010).

It is urgently required to develop adaption strategies for agriculture with climate change as till now the nexus between agriculture sustainability and adaptation to climate change is not well recognized. Some studies have shown that some mitigation measures such as using fertilizers and pesticides in more efficient ways, avoiding ploughing and management of water in rice fields, can be highly effective (Sapkota et al. 2019). The practice of Conservation Agriculture, especially for farmers with small farmlands are found to be more resilient towards abnormal rainfall patterns with the changing climate (Michler et al. 2018) and proved to be effective in moderating the loss of yield. Climate change has a negative effect on agricultural production and vice versa; however, a cause-and-effect relationship is observed between climate change and sustainable agriculture, which gets negatively affected by conventional agriculture (Agovino 2018). Long-term planning at the level of the working system is the requirement of the hour, while selecting an operating advanced farming system (Malek et al. 2017). The nexus approach contributes to achieve agriculture security, identifies trade-offs, reach synergies and facilitates proper decision making. The principle aspects of nexus, water-energy-food, can be developed by incorporating the aspects of climate change. Evidences on the effects of climate change and adaptability of the agriculture systems under numerous techniques adapted by the climate change-affected regions will help to develop nexus matrix. This nexus approach eases the path to assess cross-sectoral interactions more systematically by providing an innovative and flexible framework. This is an interesting tool to analyse and generate more interdisciplinary work by combining quantitative as well as qualitative assessment methods. The nexus approach provides stepwise process to address policy-making and showing a way to achieve the target in practice (Flammini et al. 2014). The concept of nexus research in the future is recognized through features such as methodical classification of the participating segments, linking mechanisms, multi-party decision-making and evolution of governance (Zhang et al. 2019;Tang 2019). The nexus approach in the words of Rasul and Sharma (2016) can be summarized as follows:

- To understand that the subsystems are interdependent within a system through space and time and emphasis should be on system efficiency rather than the productivity of individual sectors to provide assimilated solutions that include and add to policy objectives related to water, energy and food.
- To be familiar with the interdependence between water, energy and food resources and endorse decisions that are economically balanced. Resources should be used in a more efficient manner, which is environmentally accountable.
- To identify policy solutions which are coherent in minimizing adjustments and maximizing collaborations across sectors and encourage responses that are reciprocally valuable to enhance the potential for teamwork between and among all sectors, and public–private partnership at multiple scales.
- To safeguard policy consistency and synchronization across sectors and participants to build interactions and generate co-benefits. This will ensure more production with less resource constraints and minimum environmental impact and contribute to the long-term sustainability.
- To give more significance to the natural capital of land, water, energy and ecosystems and reassure business that is more supportive to the shift to sustainability.

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5 Heat Stress in Crops: Driver of Climate Change Impacting Global Food Supply

Richa Rai

Abstract

Climate change may cause hindrance in progress toward a vision of world without hunger. Anthropogenic activities have increased emissions of greenhouse gases with subsequent changes in temperature, rainfall patterns, and perhaps severity of extreme weather. Agriculture is inherently sensitive to climate variability. The most remarkable driver of climate change affecting agriculture is the increase of global temperature. Increase of global temperature may have a significant influence on agricultural productivity along with other consequences related to severity of the high temperature such as drought and salinity.

The present chapter highlights factor responsible for rise in temperature and its role in enhancing frequency of drought and salinity episodes which also affects agricultural production and response of increased temperature on crop's phenology, physiology, and productivity.

Keywords

Climate change · Greenhouse gases · Agriculture · Heat stress

5.1 Introduction

Populations from developing countries are likely to be the most seriously affected as nearly 50% rely entirely on agriculture. In addition, 75% of the world's poor live in rural areas, so in the future when population expands, production of crop has to be increased to sustain food security, and it has been predicted that world food production will have to increase by 70% to meet the demand of an expected population

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of 9 billion by 2050. Though it is predicted to increase global food production, in the present scenario, the world is facing major food scarcity due to decline in the yield of major cereal crops (Hasegawa et al. 2018; Fischer and Edmeades 2010).

The increasing food demand and the threat of heavy crop losses due to global climate change impose the urgency to develop strategies to improve food availability. Abiotic stresses are considered mainly in affecting plant growth, physiology, and yield, either individually or in combination. Heat, drought, greenhouse gas emissions, air pollution, and salinity are the major abiotic stresses that induce severe cellular damage in crop plants.

In nature, different developmental stages (e.g., growth, reproduction, etc.) of plants generally experience a fluctuation in temperature due to a shift in weather. However, when the temperature reaches an extreme level, it causes a serious irreversible damage to plants negatively influencing its development and fruit set.

The duration of high temperature is becoming relatively longer due to climate change. These climatological extremes impose a threat of catastrophic loss in crop productivity which may lead to a severe famine (Christensen and Christensen 2007).

Future agricultural production and thus global food security may encounter additional challenges from human population growth. Based on a mathematical modeling, cereal production in Southeast Asia and Southern Africa will be severely affected by climate change (Nelson 2009; Fischer and Edmeades 2010).

Global climate models predicted the mean ambient temperature will increase by 1–6 °C by the end of the twenty-first century. Temperatures during the growing season of wheat in the tropics and subtropics in the future may even exceed the most extreme seasonal temperatures (Battisti and Naylor 2009; Varshney et al. 2011). Latin America is predicted to experience higher temperatures and reduced precipitations throughout the continent especially in the region of Central America and the Caribbean. In Europe, most of the increase in temperature will be observed in Southern and Central parts, the most affected countries being Spain, Portugal, and Italy. High temperature may also lead to alteration of precipitation pattern causing drought and secondary salinization which also affect crop productivity. Global mean surface temperatures are projected to increase by 1.4–5 °C by 2100, and the main possible cause for increase in temperatures is rise in atmospheric CO_2 and other greenhouse gases due to anthropogenic activities (IPCC 2014). In addition to mean increase in annual temperatures, there will also be increase in the frequency, duration, and severity of periods of high temperatures (heat stress or heat waves), which could have a significant influence on ecological, economic, and sociological impacts (IPCC 2007; Barriopedro et al. 2011; Rahmstorf and Coumou 2011). It is important to identify traits which will be affected leading to yield losses due to heat stress. It is important to understand plant responses due to increase in high temperature in the coming future. The present chapter summarizes effect of high temperature on physiology, phenology, and productivity of agricultural crops.

5.2 Physiology

5.2.1 Heat Stress Signaling

Higher plants exposed to increased temperature at least 5 °C above their threshold show variations in characteristic set of cellular and metabolic responses required for the plants to survive (Izydorczyk et al. 2018) (Fig. 5.1). These changes are observed in the organization of cellular structures including organelles, cytoskeleton, and membrane function (Hasanuzzaman et al. 2013) along with decrease in the synthesis of normal proteins and the increased heat shock proteins (HSPs) (Gomez-Pastor et al. 2018) and the production of phytohormones such as abscisic acid (ABA) and antioxidants and other protective molecules (Maestri et al. 2002). The changes in ambient temperature are sensed by plants with different signaling molecules present in various cellular compartments. The increased fluidity of the plasma membrane causes upregulation of lipid-based signaling cascades to increase Ca^{2+} influx and cytoskeletal reorganization. Signaling between these routes enhances production of osmolytes and antioxidants in response to heat stress and changes in energy allocation to the photosystems (Wahid and Shabbir 2005; Allakhverdiev et al. 2008). The level of several important phytohormones like ABA, salicylic acid (SA), and

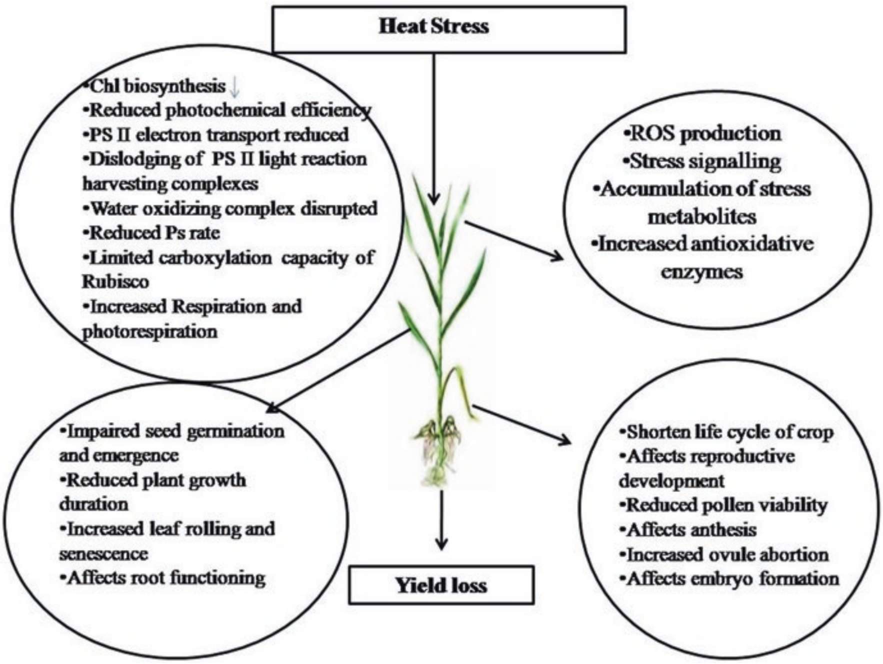

Fig. 5.1 Schematic illustration of heat stress and plant developmental responses

ethylene (ET) has increased under heat stress, while decreased in cytokinins (CK), auxin (AUX), and gibberellic acids (GAs) which cause a premature senescence of the plants (Talanova et al. 2003; Huang et al. 2016; Ibanez et al. 2017). The main reason for abscission of reproductive organs is increased ABA and ET levels and transport of auxins (AUXs) (Binder and Patterson 2009).

Similarly, an altered AUX biosynthesis in developing anthers may lead to pollen sterility (Sakata et al. 2010). Heat stress also results in the production of reactive oxygen species (ROS) and initiates oxidative stress response (Yao et al. 2017). Generating ROS is a symptom of cellular damage, where peroxidation of membrane lipids and pigments comprises membrane permeability and its function.

ROS causes damage to various cellular components like the photosynthetic apparatus hindering the metabolic activities and affecting the growth and yield by limiting metabolic flux activities (Sairam and Tyagi 2004; Xu et al. 2006). Several studies have also shown that ROS plays a key role on molecular signals stimulating plant responses to pathogen infection, programmed cell death (PCD), and even developmental stimuli (Gechev et al. 2006).

ROS/redox signaling networks in the chloroplast and mitochondria have important roles in plant adaptation to heat stress. These signals contribute to a complex interplay between organelle homeostasis and different cellular components under heat stress by controlling vital processes such as transcription, translation, energy metabolism, and protein phosphorylation (Mittler et al. 2011).

Under thermal stress, ROS such as superoxide ($\cdot O_2^-$) radicals, hydroxyl radicals ($\cdot OH^-$), and H_2O_2 are produced at the chloroplastic PS II reaction center and are scavenged by antioxidative enzymes including superoxide dismutase (SOD) (Bukhov and Mohanty 1999). Tolerant plants protect themselves from the damaging effects of ROS by synthesizing various antioxidant components which control gene expression (Abiko et al. 2005).

ROS detoxification is also determined by antioxidants such as ascorbic acid or glutathione and other ROS-scavenging enzymes such as ascorbate peroxidase (APX), catalase (CAT), and glutathione peroxidase (GPX) which are found in different cellular compartments indicating the importance of ROS detoxification for cellular survival (Mittler et al. 2004; Asada 2006).

5.2.2 Photosynthetic Pigments

Temperature stress has an independent mode of action on the physiology and metabolism of plant cells. Various physiological injuries have been observed due to elevated temperatures such as scorching of leaves and stems, leaf abscission, and senescence (Fig. 5.1). Photosynthesis serves as a global sensor of environmental stress that induces cellular energy imbalance as recorded with respect to variation in redox chemistry associated with thylakoid membranes. Photosynthetic pigments, both photosystems (PS I and PS II), electron transport system, and CO_2 reduction pathways are important components of photosynthesis, and damage to any of them is enough to influence photosynthetic mechanism of a plant (Ashraf and Harris 2013).

Photosynthetic pigments like chlorophyll play a pivotal role in light absorption, energy transfer, and electron transfer functions required to carry out in photosynthesis. Chlorophylls are made by a biosynthetic pathway in which simple molecules are used as a building block to form more complex biomolecules, and every step is enzymatically catalyzed. Plants exposed to high temperature show reduced chlorophyll (Chl) biosynthesis (Fig. 5.1). High temperature stress leads to impairment of chlorophyll (Efeoglu and Terzioglu 2009; Dutta et al. 2009) or its accelerated degradation. The main possible cause for a reduced biosynthesis is degradation of numerous enzymes involved in the mechanism of Chl biosynthesis (Dutta et al. 2009). The activity of 5-aminolevulinate dehydratase (ALAD), which is the key enzyme of pyrrole biosynthetic pathway, was found to decrease under high-temperature regime (Tewari and Tripathy 1998; Mohanty et al. 2006), suggesting high-temperature stress affects enzymes responsible in chlorophyll biosynthesis.

Percent reductions recorded in chl a content, chl a/b ratio, and sucrose content were 7%, 3%, and 9%, respectively, and significant increase in reducing sugar and leaf-soluble sugar content were 47 and 36% when soybean was exposed to high-temperature stress (38/28 °C) (Hasanuzzaman et al. 2013). Lipid peroxidation of chloroplast and thylakoid membranes also results in decline in chlorophyll pigment as observed in *Sorghum* due to heat stress (40/30 ° C, day/night) (Fig. 5.1).

Carotenoids are also found in all photosynthetic organisms and are also termed as accessory pigments as they are mainly responsible in transferring light absorbed to the chlorophyll for photosynthesis. Carotenoids are integral constituents of the thylakoid membrane and are usually associated with antenna and reaction center pigment proteins. It also serves as photoprotective agents by actively quenching the excited state of chlorophyll and checks formation of single oxygen. Studies have shown increased carotenoid content under heat stress (Asthir 2015; Buchner et al. 2015; Kislyuk et al. 2014). Apart from carotenoids, increase in the pool of xanthophylls pigments (V = violxanthin, A = anthocyanin, Z = zeaxanthin) was also a response of acclimation of the photosynthetic apparatus to heat stress. Yin et al. (2010) reported that de-epoxidation status of the xanthophyll cycle pigments V + A/A = A = Z after heat stress exposure was higher in rice plants exposed to temperature higher than 35 °C which clearly demonstrated that xanthophyll cycle plays an important role in protecting PS II from photoinhibition under heat stress.

5.2.3 Light Reactions

Photosynthesis is mainly driven by light reactions or light-dependent reactions occurring in thylakoid of chloroplast, and its end products are high-energy compounds like ATP and NADPH and dark reactions in stroma of chloroplast. Thylakoid membrane is highly susceptible to high-temperature stress (Fig. 5.1). Alterations occur in chloroplast such as altered structural organization of thylakoids, loss of grana, stacking, and swelling of grana under heat stress (Nath et al. 2013; Kaminskaya et al. 2005). Photosystem II located in the thylakoid membranes of oxygenic photosynthetic organisms is a membrane protein complex with multi-subunit that catalyzes a series of electron transfer reactions (Umena et al. 2011). The PS II is composed of 25 subunits and reaction center constituted by D_1 and D_2 proteins. Photosystem II (PSII) is considered to be one of the most susceptible components of photosynthetic apparatus to heat stress (Berry and Björkman 1980; Srivastava et al. 1997). The other factors that make PS II electron transport the most sensitive to heat stress are (i) increase in fluidity of thylakoid membranes which leads to dislodging of PS II light-harvesting complexes from thylakoid membrane at high temperature and (ii) dependence of PS II integrity on electron dynamics. Studies have shown that among photosynthetic apparatus, water-oxidizing complex (WOC), PS II reaction center, and the light harvesting complexes are initially disrupted by high temperature (Salvucci et al. 2001). Exposure to heat stress causes oxidative stress which dissociates oxygen-evolving complex (OEC) from PSII which further inhibits electron transport from OEC to PS II acceptor site.

Another cause of inactivation of PS II by heat is due to the dissociation of divalent Ca^{2+} and Mn^{2+} cations and Cl^- anion from the PS II reaction center. Heat stress causes release of extrinsic proteins such as 18 (PsbO), 24 (PsbP), and 33 kDa (PsbQ) polypeptides, and this structural change in the donor side of PSII affects degradation and aggregation of D1 proteins (Berry and Björkman 1980; Havaux 1993; Wise et al. 2004). D_1 protein is characterized as a protein of high turnover rate due to its rapid degradation when oxidized after its interaction with singlet oxygen and its replacement by newly synthesized D_1 polypeptides for maintaining PS II activity (Jarvi et al. 2015; Kato and Sakamoto 2009). D_1 protein is very susceptible to ROS. Komayama et al. (2007) found cleavage of D_1 protein which led to formation of N-terminal 23 kDa fragment, a C-terminal 9 kDa fragment, and aggregation of the D_1 protein after exposure of spinach to moderate heat stress (40 ° C for 3 min), replacing the heat-damaged D_1 with a newly synthesized copy. In chloroplast, the damaged D_1 is degraded by filamentation temperature-sensitive (FtsH) protease and Deg (for degradation of periplasmic proteins) isoforms during its rapid and specific turnover with newly synthesized D_1 protein in PS II repair cycle (Jarvi et al. 2015). Degradation of D1 protein is mainly due to FtSH protease which migrates from stroma segment of thylakoid to granal segment (Komayama et al. 2007). Heat stress impacts are also related to the thylakoid membrane integrity in conductivity and phosphorylation activity. Mathur and Jajoo (2014) demonstrated that heat treatment may induce grana destacking and the formation of inverted micelles.

Due to high temperature, electron transfer between two plastoquinone (Q_A-Q_B) is inhibited which might result due to structural change in D_1 and D_2 proteins and also changes in reorganization of the thylakoid membrane (Janka et al. 2013; Cao and Govindjee 1990). High-temperature stress leads to downregulation of the quantum efficiency of PS II due to the disconnection of some minor antenna from PS II, by enhanced photochemical quenching and aggregation of PS II complexes (Janka et al. 2013; Tang et al. 2007; Sharkey and Schrader 2006).

The fluorescence induction kinetics measurements showed higher constant yield (Fo), but lower Fm and Fv under heat stress. The increase in Fo is due to inability of the reduced plastoquinone acceptor Q_A to be oxidized completely because of retardation of the electron flow through PS II (Krause and Weise 1991) and also suggests that damage to PS II centers is not readily reversible (Krause and Weis 1988). Lowering of Fv (Fm-Fo) represents thylakoid damage, whereas a decrease in Fm indicates that heat stress could impair an electron transport involving a recombination reaction between oxidized P680 and reduced phaeophytin (Phaeo-) within photosystem II. Studies have shown that in heat stress, the ratio of variable fluorescence to maximal fluorescence (Fv/Fm) ratio and antenna size decreased which suggests that heat stress might have damaged PSII structure and blocked photosynthetic electron transport rate between PS II and PS I and also increased non-photochemical quenching (Mathur et al. 2011; Lu and Zhang 2000; Kana et al. 2008.)

5.2.4 Dark Reactions

Carbon metabolism of the stroma in the chloroplast is considered as the primary site of injury at heat stress (Fig. 5.1) (Wang et al. 2018a, b). The maintenance of cellular membrane function under high-temperature stress is essential to sustain photosynthetic and respiratory performance (Chen et al. 2010). Photosynthesis is one of the most heat-sensitive physiological processes in plants. The ability of plants to maintain leaf gas exchange and CO_2 assimilation rates under heat stress is directly correlated with its capability to tolerate heat.

Heat markedly affects the leaf water status, stomatal conductance (g_s), and intercellular CO_2 concentration. Closure of stomata under high temperature is another reason for reduced photosynthesis that affects the intercellular CO_2 concentration. Rubisco is the main enzyme involved in fixation of CO_2 in carbohydrates. Decline in photosynthesis is mainly attributed to limited capacity of Rubisco above thermal optimum. As temperature increases, the relative rate of photorespiration and dark respiration increases which contributes toward limited carboxylation capacity. The peculiar response of net photosynthesis to temperature is caused by the variations in kinetics of Rubisco and also some very unusual properties of this enzyme (Wang et al. 2018a, b).

Rubisco catalyses the first step in two competing pathways, photosynthesis and photorespiration, whose rates are determined by the rates of the carboxylase and oxygenase activities, respectively (Galmes et al. 2013). The Vmax of the carboxylase activity increases with temperature, but the affinity of Rubisco for CO_2 and the solubility of CO_2 decrease (Galmes et al. 2013; Monson et al. 1982). Photorespiratory activity increases with temperature because of decreases in both the relative specificity of Rubisco for CO_2 compared with O_2 and the relative solubility of CO_2 compared to O_2 (Jordan and Ogren 1984).

CO_2 fixation inhibited by moderate heat stress affects three measure steps of thylakoid energization: (i) non-photochemical chlorophyll fluorescence quenching, (ii) the electrochromic absorption shift, and (iii) light scattering which shows that the energy required by photosynthesis is not utilized by the Calvin cycle (Bilger et al. 1987; Law and Crafts-Brandner 1999). Other possible causes are the reduction in electron transport rate which affects the RuBP regeneration (Sage et al. 1995; Cen and Sage 2005; Yamori et al. 2005). Though the cause for the decline in the electron transport capacity above the thermal threshold remains uncertain, it may be predicted that there is increase in leakiness of proton across the thylakoid membrane and there are changes in the protein complexes of the thylakoid (Bukhov et al. 1999; Sharkey and Schrader 2006).

Heat stress also leads to upregulation of cyclic electron flow at the expense of linear electron transport which helps in maintaining ATP synthesis and the thylakoid pH gradient but causes a loss of linear electron transport as the interchain electron carriers, and photosystem I complexes are shifted from linear electron flow to support of cyclic electron flow (Bukhov et al. 1999).

The high transthylakoid proton gradient which is maintained by cyclic electron flow at elevated temperature leads to downregulation of photosystem II (PS II). Higher temperature above thermal optimum also leads to reduction in active state of Rubisco which affects photosynthetic rate at elevated temperature due to reduced activity of Rubisco activase which leads to deactivation of Rubisco at high temperature (Salvucci and Crafts-Brandner 2004). Rubisco activase maintains Rubisco in its active configuration by removing metabolites such as RuBP, carboxyarabinitol-1-phosphate, and xylulose 1,5-bisphosphate which promote carbamylation and full activity of the catalytic sites (Portis 1995, 2003).

5.3 Phenology of Crops

Heat stress impact on various plant processes leads to morphological changes in crops, affecting the developmental processes and eventually resulting in great yield loss (McClung and Davis 2010; Grant et al. 2011) (Fig. 5.1). Plant responses to heat stress differ significantly with the extent and duration of temperature and the growth stages which are exposed to the stress (Ruelland and Zachowski 2010). The primary effect of heat stress is the retardation of seed germination, poor stand establishment, and emergence in many crops including wheat by affecting embryonic cells (Johkan et al. 2011; Hossain et al. 2013). Heat stress between 28 and 30 °C may affect the plant growth duration by reducing seed germination and maturity periods (Yamamoto et al. 2008). Plant developmental responses to elevated temperature vary depending on its developmental stage.

5.3.1 Leaf and Root Development

Leaf development is strongly regulated by temperature. In *Arabidopsis*, the rate of initiation and leaf expansion and the duration of expansion increase largely with temperature in the range of 6–26 °C (Granier et al. 2002). The pace of addition of new leaves throughout a crop plant's vegetative development increases as temperature reaches its threshold temperature which is specific for different species, for example, 26 °C for wheat and 37 °C for cotton (Hatfield et al. 2011). Leaf morphology and rate of emergence are sensitive to high-temperature stress.

Soil temperature is dependent on the air temperature (Zheng et al. 1993); the projected 1.0–3.7 °C increase in average surface temperature may affect indirectly the physiology, development, and resource acquisition of the root. High temperature stress has a significant impact on the root growth, number, mass and functions like respiration (Atkin et al 2000) and nutrient uptake altering shoot and root ratio.

Elevated temperature stimulates root growth up to a species-specific threshold and significantly alters several root architecture parameters. In oilseed rape (*Brassica napus* L.), its tap root length and lateral root number increased from 10 to 35 °C, but decreased at temperature greater than 35 °C. Nagel et al. (2009) found that in plants exposed to gradients in root zone temperature, root growth along a depth gradient was modified dynamically leading to increased root density. An increased number and length of lateral root branches have been reported up to its optimal temperature, for example, up to 30 °C in sunflower and 35°C in cotton (McMichael and Quisenberry 1993), but decrease above its threshold (Jungvist et al. 2014). Heat stress reduces root water content (Liu and Huang 2000) and root hydraulic conductivity (Morales et al. 2003) affecting nutrient acquisition.

5.3.2 Reproductive Development

Plant developmental responses to elevated temperature depend on developmental stage of plant; as observed in rice, peak vegetative biomass is recorded at 33 °C, and grain formation is adversely affected if temperature exceeds above 25 °C influencing yield. Different threshold levels are required for different crops like sorghum, that is, the optimum temperature range for vegetative growth is 26–34 °C, while for reproductive growth 25–28 °C (Maiti 1996). In *Arabidopsis*, abortion of the entire inflorescence was observed at heat stress treatments of 36 °C (Warner and Erwin 2005).

Elevated temperature may impact reproductive development by altering the timing of reproductive events or by causing heat damage to reproductive structure. Reproductive developmental events tend to occur earlier when plants are grown at elevated temperature. Studies have shown that elevated temperature tends to attain maturity early; later on developmental process is delayed.

Acceleration of flowering in elevated temperature conditions may reduce the plant's ability to accumulate photosynthates and resource for successful gamete development (Zinn et al. 2010). In *Arabidopsis*, early flowering occurs in warm temperature, suggesting that temperature range plays an important role in regulating flowering time. During reproductive stages of growth, the largest reproductive developmental impact of temperature is on male gametophyte.

Male gametophyte is more sensitive to high temperature compared to pistil or the female gametophyte (Hedhly 2011) (Fig. 5.2). In rice (*Oryza sativa* L.), the maximum midday temperature above 33 °C reduces pollen viability and above 40 °C adversely affected pollen viability (Kim et al. 1996). The main cause behind reduction in pollen viability is early abortion of tapetal cells and programmed cell death in pollen mother cells under elevated temperature stress (Sakata and Higashitani 2008; Parish et al. 2012). Maize pollen viability decreases with exposure to

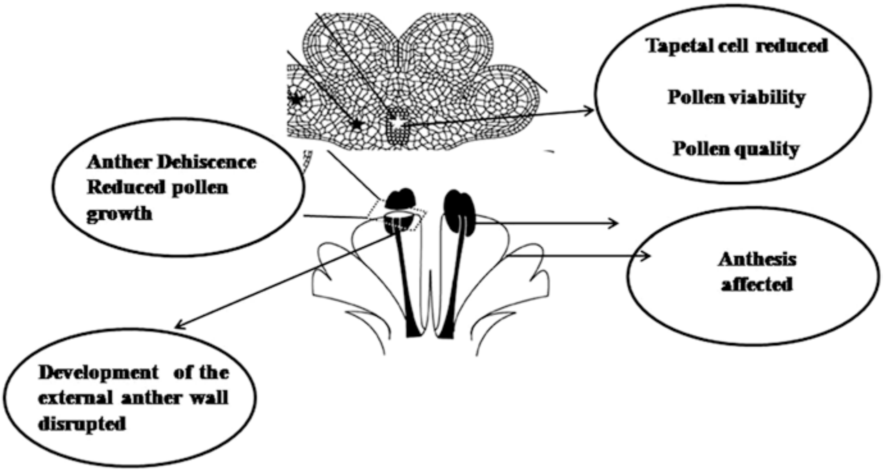

Fig. 5.2 Impact of heat stress on male gametophyte

temperatures above 35 °C (Herrero and Johnson 1980; Schoper et al. 1987; Dupuis and Dumas 1990). The effect of temperature is enhanced under high vapor pressure deficits because pollen viability (prior to silk reception) is a function of pollen moisture content which is strongly dependent on vapor pressure deficit (Fonseca and Westgate 2005). Even damage to female floral organs also contributes to loss of reproductive success. In *Arabidopsis* higher number of ovules are observed along with higher rate of ovule abortion (Whittle et al. 2009) (Fig. 5.3). The effect of elevated temperature on yield could be attributed to a reduced number of pods instead of a reduced individual seed weight or a decreased number of seeds per pod which suggests that increased pod abortion rates in response to heat stress occurred (Siebers et al. 2015). During the endosperm division phase, as temperature increased to 35 °C from 30 °C, the potential kernel growth rate was reduced along with final kernel size even after the plants were returned to 30 °C (Jones et al. 1984). Faster development of non-perennial crops results in a shorter life due to smaller plants, shorter reproductive duration, and lower yield potential due to heat stress.

Photoperiod-sensitive crops like soybean might also interact with temperature causing a disruption in phenological development. High temperature will affect pollen viability fertilization and grain or fruit formation during the reproductive stage (Hatfield et al. 2008, 2011). Chronic exposures to extreme temperature at the pollination stage of initial grain or fruit set lead to reduce yield potential.

Among different phenological stages, pollination stage is most sensitive to extreme high temperature. Maize pollen viability decreases with exposure to temperature above 35 °C (Dupuis and Dumas 1990). The effect of temperature is enhanced under high vapor pressure deficit (VPD) because pollen viability is a function of pollen moisture content which is strongly dependent on vapor pressure deficit (Fonseen and Westgate 2005).

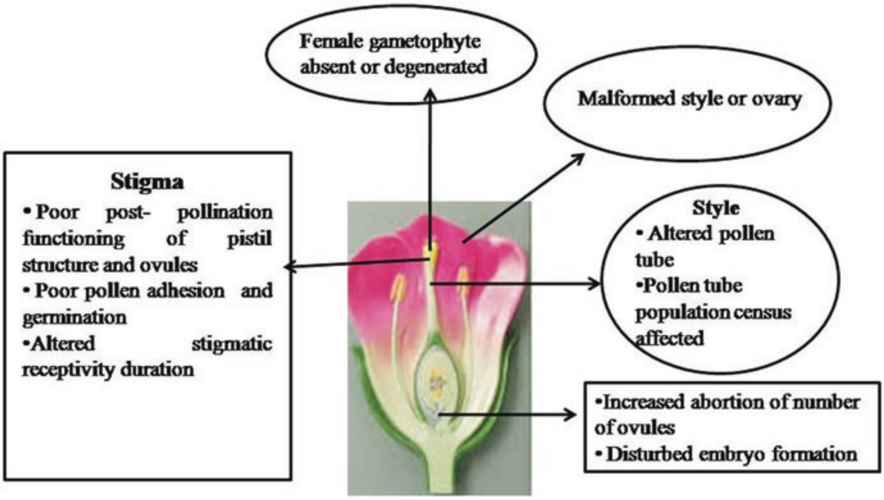

Fig. 5.3 Impact of heat stress on female gametophyte

Exposure to temperature above 30 °C damaged cell division and amyloplast replication in maize kernels which reduced the size of the grain sink and ultimately yield (Commuri and Jones 2001). Rice showed a similar temperature response as maize because pollen viability and productivity decline as daytime maximum temperature (Tmax) exceeds 33 °C and cease when Tmax exceeds 40 °C (Kim et al. 1996).

Cultivars of rice flower near midday which makes Tmax as a good indicator of heat stress on spikelet sterility dehiscence of anther, shedding of pollen, germination of pollen grains on stigma, and elongation of pollen tubes are affected, and even plants are exposed to temperature above 33 °C for 1–3 h after anthesis causing negative impact on reproduction (Satake and Yoshida 1978). Prasad et al. (2006) revealed that in rice anthesis occurs between about 9 and 11 am, and higher temperature shifts flowering and anthesis time during the day. Shah et al. (2011) suggested that variation in flowering times during the day would be a valuable phenotype marker for high-temperature tolerance. Sexual reproduction and flowering in particular have been recognized as extremely sensitive to heat stress which often results in reduced crop productivity (Thakur et al. 2010). Heat stress can reduce carbohydrates in pollen grains and ATP in stigmatic tissue (Herrero and Arbeloa 1989; Snider et al. 2009).

Thus, the additive effect of high-temperature stress to both male and female tissues may also contribute to a reduction in energy available to the growing pollen tube.

5.4 Productivity

Yield of a crop depends on the developmental stage of the crop exposed to increased temperatures. Modeling studies have suggested that throughout the twenty-first century, increase in temperature which may lead to decreased grain yields will continue for the major crops (Hatfield et al. 2011).

Global climate models predict increase in mean daily temperature to be mainly driven by rapid increase in nighttime temperature compared to daytime temperature, leading to narrowing diurnal temperature amplitude. Higher day and night temperatures induce significant negative impact on growth and development of different crops. Beyond optimum temperature, plant growth, pollination, and reproductive processes are adversely affected which ultimately leads to crop yield losses (Klein et al. 2007; Sacks and Kucharik 2011). Increases in temperature may cause yield reduction at 2.5 and 10% across a number of agronomic species throughout the twenty-first century as recorded by modeling-based studies (Hatfield et al. 2011), while Lobell et al. (2011) showed an estimated yield reduction between 3.8% and 5% through modeling studies. Wollenweber et al. (2003) exposed wheat plants to two separate periods of high temperature: first, at double-ridge stage of the apical meristem which is in a phase of transition from vegetative to reproductive development of the apical meristem and, second, anthesis. Grain yield was significantly lower in the treatments with high temperatures at anthesis and at both developmental stages. The heat stress also reduced harvest index (HI) due to lowering of grain number per plant. Season-long high-temperature stress decreases biomass production, seed number, individual seed weight, and yield of all grain crops, which is reflected in the harvest index. Another component of the climate change phenomena is the rapid increase in night temperature resulting in narrowing diurnal temperature amplitude.

Recent studies indicate significant negative impact of high night temperature on yield and grain quality among field crops (Bahuguna et al. 2016; Garcia et al. 2015, 2016; Lyman et al. 2013; Narayanan et al. 2015; Sunoj et al. 2016; Welch et al. 2010). Warmer nights negatively affect the balance between photosynthesis and night respiration rates, reducing the overall carbohydrate pool and biomass leading to reduced yield and lower HI (Bahuguna et al. 2016; Garcia et al. 2016). Among different field crops, wheat is the most sensitive cereal with its harvest index starting to drop immediately after a mean daily temperature of 16 °C, while other tropical and subtropical crops do not experience the same phenomena until 26 °C. Temperature close to 30 °C and beyond leads to complete loss of yield in wheat, while other cereals have a 10 °C higher point at which they reach similar response. Among cereals, pearl millet has the highest threshold temperature (41 °C) followed by sorghum (38 °C), rice (35 °C), and wheat (31 °C). For legumes, the ceiling temperature for cool-season dry bean was 32 °C, while for tropical soybean and peanut, it was 39 °C and 40 °C, respectively. Reproductive organs especially in cereals exposed directly to high-temperature stress such as wheat and rice have low thresholds before HI starts to drop significantly. Alternatively, crops such as peanut and soybean have much higher thresholds compared to rice.

However, recent field-based studies indicate that high night temperature has minimal effect on spikelet fertility in rice, while the major impact was reduced biomass and loss of carbohydrates in different plant parts including panicles possibly due to enhanced night respiration, leading to reduced yield and poor-quality grain (Bahuguna et al. 2016). Recently in wheat and barley studies, higher night temperature by 6 °C compared to ambient temperature which was imposed by using customized heat chambers from third detectable node till 10 days after post anthesis led to reduction in grain yield and grain number by 7 and 6%, respectively. The possible reason for reduction in yield was reduced spike numbers which indicates lesser impact of higher temperature on seed setting (Garcia et al. 2015). A large number of growth chamber studies have indicated increase in night temperature to increase spikelet sterility, thereby inducing yield losses (Coast et al. 2014; Mohammed and Tarpley 2014; Narayanan et al. 2015; Prasad and Djanaguiraman 2014).

5.5 Conclusions

Temperature influences plant growth and development especially during pollination phase as reproductive phase is highly sensitive to temperature stress but is also dependent upon plant species. It is important to understand plant performance under climate change scenario. Heat stress also affects photosynthetic apparatus of plants by inhibiting various redox and metabolic reactions taking place in PSII, PS I, Cytb6f complex, and Rubisco, changes in membrane permeability, and increased cyclic electron flow.

To overcome food insecurity under climate change scenario, it is important to develop heat stress-tolerant crops. Phenotyping approaches may be employed which classify heat stress response into the appropriate tolerance, escape, or avoidance category which is an essential first step. Secondly, it is important to establish field-based threshold temperatures which lead to reproductive damage, and it will be helpful to improve the prediction power of crop models. To develop heat-tolerant seeds, identification of traits which provides heat tolerance is of utmost importance for breeding programs. Along with genetic improvements of crop, sustainable agricultural practices are considered important in managing abiotic stress-like application of heat stress-tolerant plant growth-promoting rhizobacteria (PGPR) strains which may enhance stress tolerance in crop plants, and it may be a sustainable strategy for improving crop production under heat stress.

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6

India's Major Subsurface Pollutants Under Future Climatic Scenarios: Challenges and Remedial Solutions

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Abstract

Climatic variabilities may alter biogeochemical interactions with the subsurface environment. As of now, arsenic, fluoride, nitrate, NORMs, and hydrocarbon pollutants cover many geographical area of India. It is expected that the pollution load will increase in the upcoming decades, which may significantly affect the soil-water resources. Thus, a better understanding of behaviors of these pollutants under future climatic scenarios is imperative. In this direction, this chapter contributes the state-of-art knowledge on the challenges and issues related to India's major pollutants under current and future climatic scenarios. In the first section, the environmental fate, current expansions of these pollutants have been highlighted for polluted Indian geographical regions along with their sources, toxicity, and behaviors in the subsurface. Thereafter, a paragraph in each section is presented to elaborate the impacts of climatic variabilities on the future pollution load and its coverage. Next, the in-depth literature is discussed to solve

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the issues related to the management and remediation of these pollutants under future climatic scenarios. This chapter will help to frame and implement the remediation and management for the polluted soil-water systems under different climatic conditions.

Keywords
Indian soil-water system · Environmental fate · Distribution · Future scenarios · Remedial measures · Climate change

6.1 Introduction

A growing literature on the environmental fate and distribution of different pollutants indicates that the Indian groundwater system is highly polluted, and one can expect a greater pollutant load from increasing pollution. Thus, the management and remediation of polluted sites is an urgent need to fulfill the safe drinking water demands of the world's second largest population. The focus of this chapter is to present (a) environmental fate, (b) spatial distribution, (c) future conditions, and (d) possible remedial measures for highly prioritized pollutants reported in the Indian soil-water system.

Starting from the northern region of India, selenium is reported since 2003 by Dhillon and Dhillon (2003a), mostly in Punjab State. A high concentration zone of selenium has been reported in Punjab and Haryana (in and around northeastern Siwalik foothill zone). Depletion in groundwater may increase the selenium storage in longer unsaturated zones where the oxidizing condition will be favorable. Like selenium, naturally occurring radioactive materials (NORMs), especially ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs, has been reported in soil and groundwater in Punjab State in India (Srivastava et al. 2014). Moving towards the north and northeast, the alluvial plains of the lower Ganga have been reported to have groundwater arsenic contamination. This situation was further observed to extend in the upper and middle plains of the Indo-Gangetic regions. States such as Assam (Das et al. 2017), Bihar (Chakraborti et al. 2016a, b), Chhattisgarh (Singhal et al. 2018), Himachal Pradesh (Rana et al. 2016), Jharkhand (Alam et al. 2016), Punjab (Sharma et al. 2016), Manipur (Chandrashekhar et al. 2016), Uttar Pradesh (Olea et al. 2018), and West Bengal (Bhowmick et al. 2018) are affected with its contamination.

One can expect high hydrocarbon pollution in and around petrochemical industries, pipeline corridors, and fuel stations located in shallow and sandy aquifer regions. Furthermore, coastal zones having arid/semi-arid climatic conditions have been more vulnerable to hydrocarbon pollution due to hotspot of petroleum industries and refineries located in these regions (Gupta et al. 2018b; Gupta and Yadav 2019). While six states, namely, Andhra Pradesh, Assam, Punjab, Bihar, Haryana, and Jharkhand, use proportionately more N than the required amount highlighted for high-N concentration in groundwater (NITI Aayog, GOI2015). In the case of fluoride, various parts of Rajasthan and Gujarat are reported to have high fluoride contamination in subsurface water resources (Dhiman and Keshari 2006; Madhavan and Subramanian, 2002; Hussain et al. 2012). The literature supports a growing nature of pollutant extents in the Indian soil-water system; thus, it is needed to enhance knowledge for the management and remediation of polluted sites.

6.2 Selenium

Selenium (Se) is a metal generally located in the earth's crust. It commonly occurs in volcanic and sedimentary (coal, shale, uranium) lithological formations (Winkel et al. 2011). Some anthropogenic sources are plastics pigments, paints, enamels, inks, rubber, and coal burning. It occurs in soils in several forms, in oxidation states: selenides (Se^{2-}), amorphous or polymeric elemental selenium (Se^0), selenites (Se^{4+}), and selenates (Se^{6+}). Inorganic selenites reduce to selenium (Se^0) in high acidic and reducing subsurface, while alkaline and oxidizing conditions favor the formation of selenates (Se^{6+}). Thus, highly aerated alkaline soils that favor its oxidation start leaching of selenium where selenites and selenates are dissoluble in the host water. While selenium is water insoluble under reducing conditions and is retained in wet soil, its concentration in alkaline soil is available for plants as uptake mechanisms. Winkel et al. (2011) presented a schematic global cycle of selenium, especially highlighting the environmental pathway of Se.

The major regional background concentration of selenium is reported in a major part of northwest India, especially Punjab State (Eiche 2015). Dhillon and Dhillon (2003a) checked the quality of groundwater samples for Sein seleniferous in the region of Punjab. The selenium concentration was found to range between 0.25 and 69.5 μg/L with an average value of 4.7 μg/L. This study also highlights that shallow tube wells contain two/three times more selenium than deep tube wells. Thereafter, Bajaj et al. (2011) investigated the selenium concentration in soil and groundwater in Punjab and Haryana states. This study reports a high concentration in shallow (73 m deep) groundwater, that is, 45–341 μg/L, in two villages, Jainpur and Barwa, in Punjab. Again, Dhillon and Dhillon (2016) collected about 750 groundwater samples from different locations of Punjab and reported a selenium concentration of 0.01–35.6 μg/L. Most of the sites in and around the northeastern Siwalik foothill zone (NSFZ) and the central and southwestern zones of the state have a high concentration of Se than the average. Similarly, Lapworth et al. 2017 conducted an extensive field investigation to explore the selenium in the Bist-Doab region covering a 9000 km² area located between the Rivers Sutlej and Beas and the Shiwalik Hills in Punjab. Selenium concentration was found in shallow aquifers at 0.01–40 μg/L. It is also reported that more mobile Se is leached under oxidizing conditions. Recently, Virk (2018) investigated the Se concentration in groundwater samples from Majha belt (Amritsar and Gurudaspur District, Punjab). This study listed the values of Se concentration observed at different villages in the study area with depth of water samples. The highest concentration, that is, 0.076 mg/L, was observed in groundwater samples collected from a hand pump at Abadi Harijan Basti of Tarn Taran district. A high concentration of selenium (133–931 mg/kg; dry weight) was also observed in wheat and Indian mustard, grown in a seleniferous area in Punjab by Eiche et al. (2015). In this regard, a few studies (Dhillon and Dhillon 2003b; Bajaj et al. 2011; Eiche 2015) support that irrigation with Se-rich water is the main driving factor for the elevated Se concentration in the northwest regions of India. Another explanation is that selenium containing media originated from the nearby hills of the Shivalik range and was transported along with floodwater (Dhillon and Dhillon 2003b).

Rodell et al. (2009) reported that groundwater in North India, including the seleniferous region of Punjab, is being depleted at the rate of 4.0 ± 1 cm $year^{-1}$. Likewise, Tiwari et al. (2009) reported a loss of groundwater at the rate of 54 ± 9 km/year between April 2002 and June 2008. A similar rate of groundwater depletion was also reported by MacDonald et al. (2016). These studies highlight the highest rate of loss of groundwater from this region in India over the years. Depletion in groundwater may increase the selenium storage in more longer unsaturated zones where the oxidizing condition will be favorable, while irrigation will act as soil washing and will increase the Se concentration in the deep groundwater zone. Increasing precipitation will also increase the Se load to groundwater in the future. Mishra et al. (2014) projected a higher increase in precipitation in the northwest region of India.

Reduction of Se^{6+} to Se^0 using nanomaterial is one of the possible remediation techniques for selenium-contaminated resources (Ling et al. 2015). Zhou et al. (2016) proved that Se^{6+} is separated from water via nZVI by chemical reduction to Se^{2+} and Se^0, as well as encapsulation in the nanoparticles. Sheng et al. (2016) used nZVI on carbon nanotubes to enhance the selenite removal from water. Electrokinetic degradation of Se is another suitable remedial solution for Se removal from groundwater. Microbial bioremediation and phytoremediation are the most suitable and cost-effective in situ techniques to remediate selenium from the soil and groundwater. El Mehdawi and Pilon-Smits (2012) listed selenium hyperaccumulator species from the genera *Stanleya*, *Astragalus*, *Xylorhiza*, and *Oonopsis*, which can accumulate 1000–15,000 mg Se kg^{-1} DW (0.1–1.5% Se). Some anaerobic bacteria like fumarate reductase, nitrite reductase, hydrogenase, arsenate reductase, and sulfite reductase have been reported to reduce Se^{6+} (He et al.2018). Contracted wetlands can be effective in selenium removal from agricultural drainage (Bailey, 2017).

6.3 Arsenic

Across the globe, arsenic menace among the living communities is mainly due to its contamination in groundwater. Its elevated levels of concentration are primarily related to natural causes such as weathering and leaching from geological formations. It leaches moderately into groundwater from the earth's crust and bedrocks enriched with its ores (Vahter 2008). The mineral iron arsenate ($FeAsO_4$) is considered to be a common source of arsenic in the subsurface environment. The compounds scorodite ($FeAs_4$. $2H_2O$) and pittcite $[Fe_x^{3+}(AsO_4)_y\,(SO_4)_z]\,nH_2O$ are reported as the direct and instantaneous source of arsenic in subterranean conditions. Both of these are alteration products of mineral arsenopyrite (FeAsS), which constitute a widespread source of arsenic in natural water. Its mobilization is controlled by two major factors: (a) adsorption and desorption and (b) precipitation and dissolution of solid phase. Under reducing environment, the release of arsenic attached to iron has been considered as an important reason in sedimentary aquifer systems (Shankar et al. 2014). The generation of reducing conditions in the subsurface environment primarily depends on microbial activities in the sediments along with the abundance of organic matter (Ghosh and Sar 2013). The major factors responsible for its mobilization in the surrounding environment are diffusion of gases, sedimentation rate, and microbial reactions. Recently, oxidation of organics along with microbial-triggered reductive processes has been reported to be crucial in the mobilization of arsenic in alluvial aquifers of eastern Uttar Pradesh (Shah et al. 2017). However, high concentrations of Fe, Mn, HCO_3^- ions, NH_4^+ ions, and CH_4 gas and an absence of oxidized species such as NO_3^- and SO_4^{2-}ions are the indicators of strongly reducing conditions. Moreover, the microbial mechanisms of arsenic release require the presence of abundant organic matter in the subsurface environment.

It occurs in the subterranean environment onto the surface of iron oxides, which is an example of adsorption, and its detachment occurs through desorption. Its adsorption and release in the aquifer systems mainly occur through solid-phase precipitation and solid-phase dissolution, respectively. In alluvium plains, arsenic is present as FeAsS (arsenopyrite) along with its transformed phases such as $FeAsO_4$(ferric arsenate) and $FeAsO_3$ (ferric arsenite). It has been reported that the presence of an oxidizing agent, most commonly atmospheric oxygen (as O_2), controls the oxidation rate of arsenic containing sulfide minerals (Ghosh and Sar 2013). The increased pumping of groundwater can significantly control the oxidation of sulfide mineral and arsenic release into aquifers. Thus, increment in the discharge rate of groundwater makes the arsenic bearing sulfide mineral exposed to oxygen, which causes their oxidation and further release of arsenic to the aquifer system.

Both developed and developing countries are under a potential threat of arsenic contaminated groundwater. But India and Bangladesh are the most critically affected due to their densely populated areas. First, in the beginning of the twentieth century (1917), Argentina reported the health consequences related to arsenic after the consumption of contaminated groundwater (Smedley et al. 2005; Mihajlov et al. 2016), whereas in India, its potential health hazard was reported only in the early 1990s.

In India, the alluvial plains of the lower Ganga are reported to have groundwater arsenic contamination (Ahamed et al. 2006). This situation was further observed to extend in the upper and middle plains of the Indo-Gangetic regions. States such as Assam (Das et al. 2017), Bihar (Chakraborty et al. 2016), Chhattisgarh (Singhal et al. 2018), Himachal Pradesh (Rana et al. 2016), Jharkhand (Alam et al. 2016), Punjab (Sharma et al. 2016), Manipur (Chandrashekhar et al. 2016), Uttar Pradesh (Olea et al. 2018), and West Bengal (Bhowmick et al. 2018) are affected with contamination. From the literature survey, it is revealed that its concentration in surface and groundwater excelled from the standard permissible limit set by WHO (World Health Organization). Moreover, most of the states in North India are under a potential threat of its contamination.

Since the past few decades, the climatic variabilities have led to a decline in the groundwater table, which is a major cause of its mobilization in the aquifer system of India. Most of the ATU (arsenic treatment units) are based on the conventional removal methods (based on adsorption) in the rural areas. Its wide application and lack of protocol related to the management of toxic waste generated after the exhaustion of material are of great concern, which need attention. Recently, the formation of arsenic (AsH_3) gas has been examined in the presence of bacteria *E. coli*, which is the most common microorganism in the current living ecosystem. It has been concluded that understanding and improvement of remediation methods appear to be rational rather than to improve the problems of conventional techniques.

Several technologies are being developed for arsenic removal in groundwater since the past three decades. The most common removal techniques include oxidation and adsorption (Siddiqui and Chaudhry 2017), chemical precipitation/sedimentation (Chatterjee et al. 2017), use of ion exchange resins (Sarkar and Paul 2016), and membrane technology including reverse osmosis (Jasrotia et al. 2012). These methods are reported to have disadvantages in terms of generating highly toxic waste, which further causes its easy mobilization in the living ecosystems. Arsenic removal through coagulation/flocculation requires addition of chemicals and thereafter removal in the form of precipitates after completion of the process. This is one of the drawbacks of this technology. Also, there are possibilities of generating secondary pollutants in treated water and may cause diseases related to the pollutants. Moreover, technologies such as ion-exchange and membrane processes have limitations in terms of their higher energy consumption, high costs, and complex removal mechanisms.

Arsenic removal through adsorption has gained considerable attention despite the limitations of handling toxic waste after exhaustion of the adsorbed material. Presently, it is a widely acceptable technology due to its easy operation and less maintenance cost along with utilization of cost-effective materials (Chaudhry et al. 2017). Continuous efforts are being made in developing various nano-adsorbents to upgrade the conventional remediation techniques since the past two decades by the research community.

Recently, the in situ arsenic removal technology using permeable reactive barriers (PRBs) has drawn considerable attention and is well practiced in developed countries. This mode is considered an environmentally friendly, cost-effective, and reliable technology compared to ex situ mode of treatment. The nanoscale zero valent iron (nZVI) has been explored in the PRB system and is considered to be an extension of the conventional ZVI technology (Kanel and Al-Abed 2011). In the subsurface environment, nZVI has proved to be one of the most popular adsorbents for the removal of dominant arsenic species (Ranjan et al. 2018). Further, long-term performances and the cost-effectiveness of reactive barriers are also of concern. Although PRBs have been proved to be promising technology compared with the conventional mode of treatment methods for arsenic removal, there are still significant limitations that occur due to the geochemical and physical characteristics of contaminated sites. The major limitation is the lack of information on the long-term effectiveness of large-scale remediation systems. Therefore, it has not yet been approved by USEPA (United State Environment Protective Agency) till now.

6.4 Naturally Occurring Radioactive Material (NORM)

There are a few theories of high uranium concentration in southwest Punjab. One of them states that percolation of irrigation water dissolves CO_2 from plant respiration and microbial oxidation from the root zone (as area is agriculture dominated) and forms carbonic acid. Such carbonic acid dissolves the calcium carbonate (calcareous soil) to produce bicarbonate which leaches uranium from soils to the groundwater (Alrakabi et al. 2012). Phosphate fertilizers (containing uranium) are another possible source to soil/groundwater in these regions. Acidic magmatites and metamorphites are the reported primary natural sources of uranium, originate soluble U^{6+} by dissolving to groundwater, while insoluble U^{4+} get deposited under redox conditions. The Siwalik sedimentary formations host significant uranium mineralization in these regions (Patnaik et al. 2016). Regions of high alkalinity/salt are driving the uranium solubility in Tamil Nadu state. Thivya et al. (2014) found high U and ^{222}Rn levels in regions of granite formations followed by Fissile hornblende biotite gneiss and Charnockite formation.

Like selenium, naturally occurring radioactive material (NORM), especially ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs, has been reported in soil and groundwater in Punjab State, India (Srivastava et al. 2014). Singh et al. (2009a, b) reported about 0.9–63 ppb uranium concentration in groundwater samples near Amritsar-Bathinda, while Kumar et al. (2011) reported 73.1 ppb, which is five times higher than the permissible limit prescribed by the WHO (WHO, 2011). Kumar et al. (2011) analyzed the subsurface water samples for uranium concentrations collected from different locations in Bathinda, Mansa, Faridkot, and Firozpur of Punjab State. This study reported a range between <2 and 644 μg/L with a mean value of 73.1 μg/L concentrations of uranium in this study area. Alrakabi et al. (2012) reported a maximum concentration of 212 ppb of uranium in groundwater samples collected from Baluana village near Bathinda city, Punjab. Other than Punjab, high uranium and radon (^{222}Rn) concentrations have been reported in Nalgonda district, Andhra Pradesh, by Keesari et al. (2014). In Karnataka, high uranium in the groundwater in Kolar district has been reported by Babu et al. (2008). Likewise, Thivya et al. (2014) reported high concentrations of uranium and radon (^{222}Rn) in Madurai district, central Tamil Nadu. Das et al. (2018) reported co-occurrence of uranium in sediments of the Brahmaputra floodplain, but this study was not analyzed for uranium concentration in groundwater.

As mentioned in the section on the future scenarios of the regions in Punjab, it is expected that precipitation will increase in the future. A study by Kooperman et al. (2018) suggested that flooding event (expected to increase in future) will increase CO2, can reduce stomatal conductance and transpiration, and leads to increased soil moisture in subsurface. High soil moisture content may enhance the dissolution of

CO_2 from the root zone and also support microbial decompositions at a high rate forming more carbonic acid in the subsurface. Large amounts of carbonic acid will accelerate uranium leaching. As the groundwater table is declining, uranium may get more adsorbed in soil in large unsaturated zones—this, however, is still not clear.

Generally, soil washing with appropriate reagent and absorbent (resin, activated carbon, activated silica, titanium adsorbent) has been reported earlier to decontaminate NORM from the polluted sites. Kim et al. (2016) performed soil washing with sulfuric acid with and reported an adsorption of 90% of the uranium on the S-950 resin and desorbed 87% on S-950 by adding 0.5 M Na_2CO_3 at 60 °C. Phillips et al. (2008) performed batch and column experiments using synthetic resin for removal of uranium from groundwater. They reported that Purolite A-520E anion-exchange resins removed more uranium from high-pH (pH = 8) and low-nitrate-containing synthetic groundwater in batch tests than metal-chelating resins (Diphonix and Chelex-100), while the metal-chelating resins are more effective in the case of acidic (pH = 5) and high nitrate containing groundwater. On the other hand, application of zVI can be an effective approach for uranium removal from groundwater. Noubactep et al. (2005) reported high removal of uranium from groundwater in batch experiments having ZVI (FeS_2 and MnO_2). Bhalara et al. (2014) reviewed physical remediation techniques generally used to decontaminate the soil-water resources. One can refer to his contribution for more details on physical remediation techniques.

However, physical-chemical techniques need more remediation time and cost due to high electricity demand compared to bioremediation techniques. There is a growing literature which reports that microbial and phytoremediation are the most suitable and cost-effective remediation approaches to uranium-contaminated sites (Bhalara et al. 2014). A range of microbial communities like Pseudomonas MGF-48, a Gram-negative, motile, oxidase negative, catalase positive, yellow pigmented bacterium, have been found to accumulate uranium with high efficiency (Malekzadeh et al. 2002). Newsome et al. (2014) highlighted different microbial-moderated mechanisms like bioreduction, bio-mineralization, biosorption, and bioaccumulation of uranium remediation. Khijniak et al. (2005) and Fredrickson et al. (2000) demonstrated the microbial reduction of poorly soluble U(VI) as uramphite using *Thermoterrabacterium ferrireducens* and as metaschoepite using *Shewanella putrefaciens* CN32, respectively. Some researchers reported *Pseudomonas* species as effective bio-mineralization. One can refer to the detailed bioreduction of uranium from soil-water resources reviewed by Newsome et al. (2014).

6.5 Petroleum Hydrocarbon

Petroleum hydrocarbons pose potential threats to humans as well as to the ecological health (Gupta and Yadav 2017a, b, c). These pollutants are released by several industrial activities like accidental spillage, industries, and leaks from underground storage tanks, agricultural practices, and poor waste disposal in landfills. This may cause ultimate sinks for such toxic pollutants into major components of the soil-water system. When released at the (sub)-surface, petroleum hydrocarbon generally referred to as non-aqueous phase liquids (NAPL) starts moving downward through the unsaturated zone before meeting the groundwater table where it forms a pure phase pool in the capillary fringe zone (Essaid et al. 2015). This pure phase of NAPL then migrates in lateral and transverse directions in capillary fringe and starts dissolving into the subsurface water and moves to down-gradient locations due to advection, diffusion, and dispersion of mass transport (Gupta et al. 2013, 2017, 2018a, b, 2019). Transport of the dissolved LNAPL through interconnected pores is predominantly governed by hydrodynamic dispersion under varying groundwater flow regimes posing a potential risk to the receiving environment (Yadav and Hassanizadeh 2011). One can refer to Essaid et al. (2015) for more details on the fate and transport mechanisms of organic hydrocarbons in subsurface.

In India, petroleum production and refineries are increasing fast. According to the annual report, 2017–2018, of the Ministry of Petroleum and Natural Gas, Government of India, 247.6 MMT per year addition capacity of all refineries of India was developed in 2017. Most of the petroleum production industries and refineries are located in the coastal zones having arid and semi-arid climatic conditions. One can expect high pollution of hydrocarbons in and around petrochemical industries, pipeline corridors, and fuel stations located in shallow and sandy aquifer regions (Gupta and Yadav 2017a, b; Mustapha et al. 2018).

The fate and transport of contaminants including petrochemicals are directly affected by climate change conditions (Gupta et al. 2018c). Environmental variability and changes affect groundwater resources considerably and are responsible for frequent fluctuations in groundwater table and its flow velocities particularly in shallow unconfined aquifers (Sulaymon and Gzar, 2011). Rapid groundwater table fluctuations along with high pore-water velocities are expected in shallow aquifers, causing the enhanced mobilization of pollutants (Dobson et al. 2007). The water table fluctuations cause the (up)-downward movement of the plume and cause entrapment in pore space, which increases the wide coverage of the pollutant masses. Thus, pollutants entrapped in the form of isolated blobs or ganglia increase the water interfacial area, which enhances dissolution (Soga et al. 2004). Pollutants trapped in the subsurface become the residual act as long-term pollution sources, which degrade very slowly (Abhishek et al. 2018a, b). The distribution of water and air has direct effects on the pollutant fate and transport as well as soil microbial processes responsible for degradation of subsurface pollutants especially organic pollutants. The shortage of soil moisture content increases in greater air-filled porosity, which significantly improves the oxygen mass transfer to pollutant-degrading microbial assemblage (Alvarez and Illman 2006). Likewise, bioavailability of pollutants is a temperature-dependent mechanism. Low-temperature conditions may reduce volatilization and decrease water solubility of pollutants (Margesin and Schinner 2001). Temperature plays a significant role in controlling the nature and extent of microbial metabolisms that are responsible for degradation of several pollutants, especially hydrocarbons (Yadav and Hassanizadeh 2011).

Successful implementation of remediation has been well documented for many polluted sites with petroleum hydrocarbons. Bioremediation offers several advantages and limitations compared to traditional site remediation approaches such as pump-and-treat or soil excavation followed by other physiochemical remediation techniques (Gupta and Yadav 2017a, b, c). There are two principal biological approaches to treat the contamination in situ: traditional and engineered bioremediation systems that rely on microbial metabolism for site cleanup and phytoremediation, which relies on vegetation (Basu et al. 2015). Plant-assisted bioremediation refers to the use of selective plant species for the targeted pollutant to mitigate the toxic effects and removal of pollutant mass from (sub)-surface. This technique uses the plant–geochemical interaction to modify the polluted site and also supply (micro)-nutrient, oxygen into the subsurface for better performance of petrochemical degrader on targeted pollutants (Susarla et al. 2002). The plant–geochemical interaction enhances the (1) physical and chemical properties of sites, (2) nutrient supply by releasing root exudates, (3) aeration by transfer of oxygen, (4) intercepting and retarding the movements of chemicals, (5) the plant enzymatic transformation, and (6) resistance to the vertical and lateral migration of pollutants. One can refer to Gupta and Yadav (2017a, b, c) for details on bioremediation of hydrocarbons in the subsurface.

6.6 Nitrate-N

Nitrate is emerging as one of the potential groundwater contaminants due to its intensive use as chemical fertilizers required for increasing the agricultural production to cater to the demands of a growing population and its high mobility through variably saturated soils (USEPA 1990). Other anthropogenic sources of nitrate loading to groundwater are sewage, septic tanks, landfills, and open drains. Nitrate contamination in the world's groundwater poses potentially serious health hazards to mankind at large (Suthar et al. 2009). Compared to point source pollution, the non-point source pollution is more difficult, related to monitoring and enforcement of mitigating controls, due to the heterogeneity of the subsurface porous media at large scales (Gupta and Joshi, 2017; Gupta and Sharma, 2018). Therefore, better understanding of the nitrate fate and movement in the entire vadose zone are essential to assess the long-term impacts of nitrogen fertilizer management practices on the groundwater quality. This is even more crucial for the dry regions where the irrigation return flow is a major component of recharge to local groundwater resources. As heterogeneity is ubiquitously present in the entire vadose zone, non-uniform/preferential flow takes place leading to the non-equilibrium solute transport through the soil pores (Vogel et al. 2010). These non-equilibrium conditions play a very important role in processes of contaminant fate and transport through the vadose zone (Simunek et al. 2003). Generally, the preferential flow and non-equilibrium solute transport hasten the movement of (sub)-surface contaminants to the groundwater through the vadose zone (Gardenas et al. 2006;Wang 2008). Another key obstacle in assessing nitrate emissions to groundwater is the often-significant thickness of the variably saturated zone (Harter et al. 2004; Kumari et al. 2019).

In the Indian context, high nitrate concentration has been observed in the groundwater of the densely populated areas of Andhra Pradesh, Bihar, Chhattisgarh, Delhi, Goa, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Karla, Maharashtra, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, Uttarakhand, and West Bengal (CGWB report 2010). Greater than 33% of water samples in Punjab and Haryana have nitrate levels above the desired limits (Malik 2000). A study by the Karnataka rural water supply and sanitation agency in 2004 showed that nitrate contamination of groundwater is a problem in most of districts of the state. Similarly, severe nitrate groundwater contamination is reported in the rural areas of Rajasthan (Suthar et al. 2009). According to the groundwater yearbook of states, 2015–2016, by CGWB, the nitrate concentrations in some parts of the above highlighted areas are as high as 1500 ppm nitrate load in groundwater, which has grave health impacts. Recently, the government of India has targeted to double the income of farmers by 2022. This cannot be accomplished by ignoring the intense use of fertigation in the cropped land of the country. It is noteworthy that a recent report released by the National Institute of Agricultural Economics and Policy Research indicated that one-third of the major states in India apply excessive nitrate fertilizers, while six states, namely, Andhra Pradesh, Assam, Punjab, Bihar, Haryana, and Jharkhand, use proportionately more N than the required amount (NITI Aayog, GOI2015).

Based on the project report of Mishra et al. (2014), the temperature will increase in all parts of India in the future and in all the cropping sessions. By watching the increased evapotranspiration in the region which may decrease the water infiltration and groundwater recharge, one can expect a decreasing pattern of nitrate leaching in the future climate scenario. However, there are limited studies on nitrate behavior in the subsurface for these regions.

As an alternative to pump and treat, Harter et al. (2012) highlighted two possible approaches: enhanced in situ biological denitrification (EISBD)/in situ redox manipulation (ISRM) and permeable reactive barriers (PRBs) as in situ denitrification techniques. To remediate nitrate (non-point sources) from groundwater, a growing literature suggests that phytoremediation and constructed wetland can significantly help to enhance the denitrification process. Furthermore, providing the combination of subsurface condition (oxygen, nutrients, etc.) will help to accelerate denitrification to fully degrade nitrate. Robertson and Cherry (1995) demonstrated the in situ nitrate removal using PRBs made of sawdust and achieved >90% removal efficiency in the field. One can refer to Harter et al. (2012) for more details of possible remedial measure for shallow and deep zone nitrate contamination.

6.7 Fluoride

Fluoride is the 24th most common element in the Earth's crust, and is found in both organic and inorganic forms, although inorganic fluorides are more commonly found. Natural weathering of fluoride minerals is the primary source of inorganic fluoride. Fluorite (CaF2), fluorapatite ($Ca_5(PO4)_3F$), and cryolite (Na_3ALF_6) are the primary fluoride minerals found geogenically, and volcanoes constitute the second major source releasing gases with hydrogen fluoride (HF) into the environment (Symonds et al. 1988; CEPA 1994). Marine aerosols are the third major natural source (CEPA 1994). In water, inorganic fluorides more often than not stay in solution (as fluoride ion) under conditions of moderately low pH and hardness and within the nearness of ion-exchange materials such as bentonite clays and humic acids (CEPA 1994). Inorganic fluorides in solution may in any case be expelled from the aquatic phase by the precipitation of calcium carbonate, calcium phosphate, calcium fluoride, and, indeed, magnesium fluoride (Stumm and Morgan 1996).

Fluoride is naturally found in the water. Globally, the wellbeing of millions of individuals is debilitated by endemic fluorosis due to utilization of groundwater contaminated with F^- (UNICEF 2008). At the worldwide scale, high F^-concentrations (i.e., >1.5 mg/L) are found in groundwater in China, Syria, Jordan, Ethiopia, Sudan, Tanzania, Kenya, and Uganda (Ando et al. 2001). In India, groundwater contaminant with $F^-$is well documented at various places in the states of Rajasthan, Gujarat, Karnataka, Andhra Pradesh, Madhya Pradesh, Chhattisgarh, Uttar Pradesh West Bengal, Bihar, Haryana, Orissa, Punjab, Haryana, Delhi, Jharkhand, Maharashtra, and Assam (CGWB 2010). Different parts in Rajasthan and Gujarat have also been identified with high fluoride concentration in groundwater (Dhiman and Keshari 2006; Madhavan and Subramanian 2002; Hussain et al. 2012). In spite of the fact that various studies have been conducted in this region, the rural areas are still lacking in understanding of fluoride contamination and its impact on humans. In spite of the fact that geological sources contribute the maximum to the fluoride contamination in water, other factors such as porosity and acidity of the soil and rocks, temperature (i.e., semi-arid climate), the action of other chemicals, advanced stage of groundwater development, and the depth of wells also play a significant role in fluoride release (Ranjan et al. 2013). The sources of fluoride in groundwater through fluoride-rich rocks are fluorspar (CaF2), cryolite (Na3AlF6), fluorapatite (Ca5(PO4)3F), and sellaite (MgF2). The F^-concentrations in groundwater run from well beneath 1.0 mg/L to more than 35.0 mg/L (IPCS1984).

A concern in this connection, albeit within a longer time perspective, is climate change. Climate change may affect the distribution and concentrations of fluoride (Kumar et al. 2006; Mall et al. 2006; Turner and Annamalai 2012). The climate is expected to be warmer but most of India is also expected to receive more rainfall. Runoff will remain more or less as of now except in the northwest (Mall et al. 2006; Turner and Annamalai 2012). Rivers like Narmada and Sabarmati are expected to have decreased runoff (Mall et al. 2006). These areas already have groundwater with excess fluoride and endemic fluorosis, and this will probably be an increasing problem in the northwestern part of India. Further, change in land use causing altered abstraction and recharge patterns impacts groundwater quality degradation significantly through both point and diffuse sources of pollution (Lerner and Harris 2009). Therefore, climate-driven land use changes will likely affect the water quality and dissolved fluoride concentrations in bedrock aquifers (Bondu et al. 2018).

Fluoride has various negative effects on both humans and plants; thus its monitoring and mitigation are necessary. The physical and chemical methods of defluoridation are adsorption, ion-exchange, membrane process, and precipitation. A famous precipitation technique is "Nalgonda Technique," which is named after a district in Andhra Pradesh where it was used for the first time for defluoridation of drinking water at community level developed by CSIR-National Environmental Engineering Research Institute, Pune. This method is based on addition of alum and lime, leaving aluminum complexes in the water that could be toxic (Meenakshi 2006). However, using stable aluminum compounds could offer a good solution (Karthikeyan and Elango 2009). Defluoridation using biological agents such as biosorbent, phytoremediation, and bioremediation is useful due to the following reasons: easy availability, eco-friendly, and efficiency.

Muralidharan et al. (2011) subsequently recommended water harvesting in the upstream areas of catchments to dilute the groundwater. Furthermore, recent research has studied the efficiency of recharge from small percolation tanks in hard rock terrain in India (Boisson et al. 2014: Massuel et al. 2014), which is typical for areas with elevated fluoride levels in groundwater. It turns out that around 60% of the water collected water percolates to the ground. Even if rainwater harvesting does not result in acceptable concentrations of fluoride in the groundwater, it is important as it will decrease the demand on the capacity of filters and other ex situ technologies.

6.8 Current Practice of Arsenic, F, and Other Pollutant Removals in India

After discussion of the pollutant coverage and expected behaviors in near future/under climate change condition, this section focuses on highlighting the current practices for removal of these pollutants. In the case of arsenic, adsorption-based units are currently installed in some part of affected areas of West Bengal and Bihar. Sarkar et al. (2008, 2012) implemented community scale As removal units made of stainless steel column packed with ~100 L of adsorbent in a village in West Bengal. The dissolved air helps oxidize the ferrous iron in the raw water to form fine precipitates of HFO. Precipitation of HFO adsorbs arsenic, and the remaining arsenic in the water is removed by a bed of adsorbent media contained within the rest of the unit. A schematic diagram of an arsenic removal unit is presented in Fig. 6.1. Likewise, defluoridation units (DDUs) are installed in several parts of India to decontaminate fluoride-contaminated groundwater for drinking. Most of the DDUs are activated alumina-based units made for household scale (Chauhan et al. 2007). The knowledge gained in this book chapter will be helpful for planning the management and

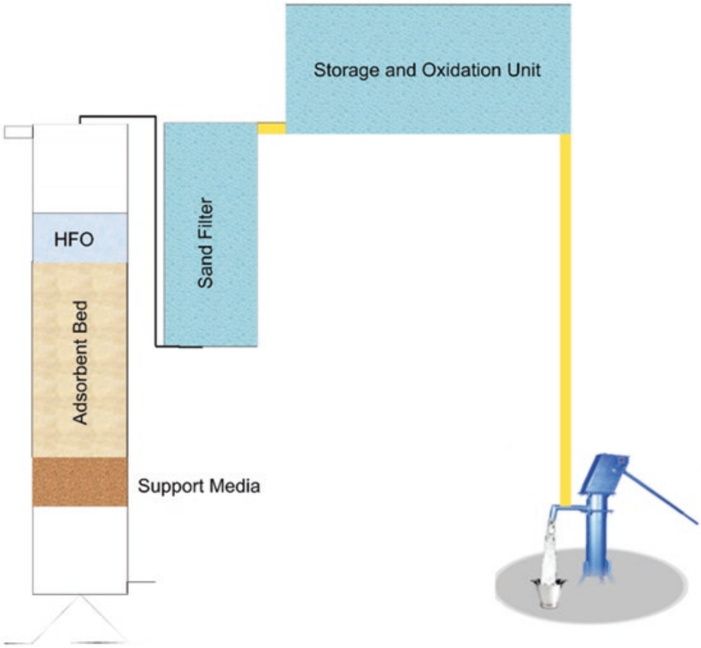

Fig. 6.1 Arsenic removal unit based on adsorbent treatment

remediation of polluted sites. Furthermore, this will help to frame policies for new schemes by the government of India like Swachh Bharat mission, smart city, national mission for clean Ganga, rural development, and so on (Table 6.1).

6.9 Concluding Remarks

The management and remediation of the Indian soil-water system should be our first priority to fulfill the safe groundwater demand of the world's second largest population. In this regard, the focus of this chapter is to present a review of the literature on environmental fate, spatial distribution, future scenarios, and remedial measures for a wide range of groundwater pollutants with emphasis on the conditions of the Indian aquifer system. Coverage of a wide range of pollutants including selenium, naturally occurring radioactive materials, arsenic, and so on helps to provide the current update to environmental scientists and geochemists. It is hoped that this chapter will significantly enhance the existing knowledge of the reader of this book on the Indian groundwater system. However, there is need to present more details of these pollutants for different agro-climatic regions. The following recommendations are listed based on the information collected here:

Table 6.1 Summary of studies reported on As/F contamination in different states of India

State	District	Concentration range	Key findings	References
West Bengal	9 districts: Maldah, Murshidabad, Bardhaman, Hugli, Howrah, Nadia, North 24-Parganas, Parganas, and Calcutta	>50 μg/L	Out of 9 As affected district, 7 districts reported high health issues (skin lesions)	Chowdhury et al. (2000)
West Bengal	Ganges-Brahmaputra-Meghna deltaic alluvium	0–0.29 mg/L	Fe(II)-Fe(III) cycling is the dominant process for the release of As from aquifer sediments to groundwater	Chatterjee et al. (2010)
Bihar	Bhojpur (Ara-Semria Ojha Patti)	>1000 μg/L	56.8% groundwater samples exceeded arsenic concentrations of 50 μg/L, with 19.9% >300 μg/L	Chakraborti et al. (2003)
Uttar Pradesh	Ballia, Varanasi, and Gazipur	>300 μg/L	Older tubewells had greater chances of As contamination	Ahamed et al. (2006)
Punjab	Shivalik Hills (Zone-I); Indo-Gangetic Plain (Zone-II); Arid area Southwest (Zone-III);	3.5–688 μg/L	Zone-I: 3.5–42 μg/L; Zone-II: 9.8–42.5 μg/L; Zone-III: 11.4–688 μg/L	Hundal et al. (2007)
Assam	Dhemaji district	0–0.016 ppm	High As-concentration was recorded in dry season than in wet season	Buragohain et al. (2010)
Andhra Pradesh	Anantapur (southwestern part)	0.56–5.80 mg/L	Dissolution of fluoride bearing minerals by high ET and low hydraulic conductivity	Rao and Devadas (2003)
Orissa	Nayagarh, Singhpur, and Sagaragan	>1.5 mg/L	Mixing of hot spring water with groundwater	Kundu et al. (2001)
Rajasthan	Ajmer (whole district)	0.16–16.9 mg/L	Calc-gneiss, schist, granite, quartzite, phyllite, and limestone	Vikas et al. (2009)
Rajasthan	Nagaur (Nawa Tehsil)	0.3–5.91 mg/L	Bed rock	Hussain et al. (2012)

1. There is an urgent need to establish/frame a satiable management and remediation plan/approach for all kinds of pollutants in the highlighted hotspot regions, for example, selenium in the northwestern states.
2. One can expect more groundwater quality threats in the near future due to high mobilization/loading of these pollutants; thus there is need to enhance the

knowledge of the common people to include more participation from the local to the higher level in management and remediation of polluted sites.

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7 Phosphorus Sorption Characteristics of the Surface Sediments from Industrially Polluted GBPS Reservoir, India

Bijendra Kumar and Anshumali

Abstract

Various kinetic models and isotherm have been used for deciphering mechanism of phosphorus (P) sorption on surface sediments of polluted freshwater bodies. The P sorption kinetics and equilibrium isotherm and the relationship between phosphorus sorption parameters were studied in 24 industrially contaminated surface sediments of Govind Ballabh Pant Sagar (GBPS) reservoir, India. The results showed that P adsorption on the sediments mainly occurred within 10 h and then reached equilibrium in 48 h; phosphate sorption rates of 0–0.25 h were the highest over 48 h and suggested quick sorption process; and the pseudo-second-order rate model showed the kinetics of P adsorption with high correlation coefficients. Native adsorbed phosphorus (W_{NAP}) and adsorption equilibrium concentration (C_{EPC}) were found to be high in surface sediments of the most polluted upstream region. The surface sediments showed maximum adsorption ($Q_{max,}$ mg kg^{-1}) with 0.80 mg L^{-1} phosphorus concentration. The equilibrium concentration of phosphorus (C_{eq}) was more than the C_{EPC}, while the W_{NAP} values were less than Q_{max}. The positive regression between W_{NAP} and C_{EPC} and K_p (partition coefficient) and Q_{max} indicated that surface sediments would act as a sink and adsorb phosphorus from overlying water in the GBPS reservoir.

Keywords

Phosphorus · Industrial pollution · Reservoir · Adsorption kinetics · Isotherm

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7.1 Introduction

Sedimentary P is mainly originated from watershed geology, hydrometeorological condition, and anthropogenic inputs (Smal et a1. 2013; Sulu-Gambari et al. 2018; Kumar and Anshumali 2019). The worldwide yearly phosphorus (P) misfortunes from the lithosphere into freshwaters are assessed at 18.7−31.4 MMT P year^{-1} (Compton et al. 2000). Phosphorus (P) is a primary limiting nutrient, which is available as inorganic PO_4^{-3} and assimilated in the formation of complex biomolecules and cellular energetic (Zhou et al. 2005; Guo et al. 2017). The enrichment and biogeochemical transformation of inorganic P lead to eutrophication and degradation of water quality of freshwater ecosystems (Babu and Ramaswamy 2017; Song et al. 2017).

In recent years, the sediments are identified and used in the assessment of biogeochemical processes associated with P release and burial (Katsaounos et al. 2007; Mendes et al. 2018). Inorganic phosphorus (PO_4^{-3}) can be found in sediments either as part of a mineral or precipitated phosphate salt (Han et al. 2011; Liang et al. 2018). The phosphate adsorption at the sediment–water interface is a significant procedure that influences phosphorus transport, bioavailability, and fixations in the overlying water (Wang et al. 2005; Chen et al. 2016; Kraal et al. 2017). Various kinetic models (pseudo-first-order and pseudo-second-order) and isotherm have been suggested for deciphering the mechanism of P adsorption/desorption (Azizian 2004). The equilibrium adsorption process of sediments from a different origin is usually described by the Langmuir adsorption isotherm, the Freundlich adsorption isotherm, or the linear adsorption isotherm (An and Li 2009). The kinetic parameters acquired can be used to determine P sorption capacity, rate constant, and correlation coefficient (Shoja et al. 2017; Cao et al. 2019). The adsorption capacity and adsorption efficiency are related to the organic matter, the Fe/Al (hydr)oxide, calcium carbonate ($CaCO_3$), particle size, sources of sediments, depth of water body, industrial pollution, etc. (Jin et al. 2013; Huang et al. 2015; Flower et al. 2016; León et al. 2017). The sediment pH plays a dominant role in P sorption, when the pH ≥ 8, and Ca^{2+} tends to grab P and precipitate from overlying water (Anshumali et al. 2012; Li et al. 2013; Meng et al. 2014; Huang et al. 2016). The native adsorbed phosphorus might be released from sediments under various environmental conditions, in which case these sediments become a source of phosphorus (Zhang et al. 2016; Li et al. 2016; Xie et al. 2019). The sorption features of P at the sediment–water interface have therefore been the subject of widespread research because of their efficient role in preserving a bioavailable P pool (Samanta et al. 2015; Aissa-Grouz 2018; Huang et al. 2018).

The Govind Ballabh Pant Sagar (GBPS) store is one of the biggest repositories in India, developed on the Rihand River, a tributary of the Son River. The GBPS reservoir is lifeline for major industries (Northern Coalfield, National Thermal Power Plants Units, Reliance, ESSAR Thermal Plants, HINDALCO, and Cement Industries), rural and urban centers, and irrigation usages in the middle Gangetic Plain (Anshumali et al. 2014). These industrial and man-made activities are associated with the direct discharge of wastewater, increased sediment deposition, soil erosion, and surface runoff into the GBPS. Recently, quantitative morphometric characterization reveals immediate attention for the restoration and conservation of the Rihand River Basin to sustain the carrying capacity of the GBPS reservoir (Kumar et al. 2018). Numerous studies concentrated on geochemistry, community structure, primary productivity, water quality, and trace metal pollution (Jamal et al. 1991; Mishra et al. 2008; Khan et al. 2013); there is surprisingly no information reported on P content and phosphate sorption characteristics of surface sediments. In view, the objectives of the present study were (1) to investigate the P sorption kinetics and equilibrium isotherm and (2) to explore the relationship between phosphorus sorption parameters of the surface sediments of GBPS reservoir. These studies try to reveal further the mechanism of phosphorus exchange on the water–sediment interface, the geochemical behavior of phosphorus, and its bioavailability in an aquatic environment polluted by anthropogenic activities.

7.2 Material and Methods

7.2.1 Study Area

In 1962, a large-scale dam banked up the water of the River Rihand a tributary to Sone, which in turn joins the Ganga River on its right flank. The dam is known as Rihand dam, and the reservoir was named as Govind Ballabh Pant Sagar (GBPS); the length and height of the dam are 934 m and 91 m, respectively; total catchment area is 5148 km^2, and total storage capacity is 10.6 bcm. The global positioning of study area lies at 24°00′–24°12′ N and 82°38′ to 82°58′ E, and the mean sea level ranges from 265 to 298 m (Fig. 7.1). The Kachan, Ballia Nala, Dongia Nala, Murdhwa Nala, and various fly-ash ponds contribute polluted wastewater and sediment load; and perennial streams mainly Mayer, Rihand, Baran, and Azir rivers contribute freshwater in the GBPS reservoir.

The GBPS catchment is a part of Vindhyan supergroup, made for the most part out of low plunging arrangements of sandstone, shale, and carbonate, with a couple of combination and volcaniclastic beds, isolated by a noteworthy provincial and a few nearby unconformities (Bhattacharyya 1996). Topographically, the stones of Mahakoshal and Dudhi gatherings of Palaeoproterozoic age and Damuda gathering (Gondwana supergroup) of Permian to Carboniferous age are uncovered in the investigation region (GSI 2009) (Fig. 7.1). The stones of Mahakoshal group are made of phyllite with quartzite, andalusite mica schist, limestone, corrosive meddlesome, metabasic rocks, cherty quartzite, slate, marble, and tuff. The stones of Dudhi bunch overlie the Mahakoshal group and comprise medium to finely grained diorite, dim granodiorite, epidotized pink tourmaline gneiss, leucocratic rock, and enclaves of metamorphites, amphibolites, rock gneiss, migmatite, and metasedimentaries. The stones of Damuda group comprise coarse ferruginous sandstone intercalated with coal creases and green shale. The sum and creation of mud minerals, especially the kaolinite/illite (K/I) proportion, in the suspended residue/aggregated sediment of the store is a marker of its provenance (Friedman and Sanders 1978). In view of the

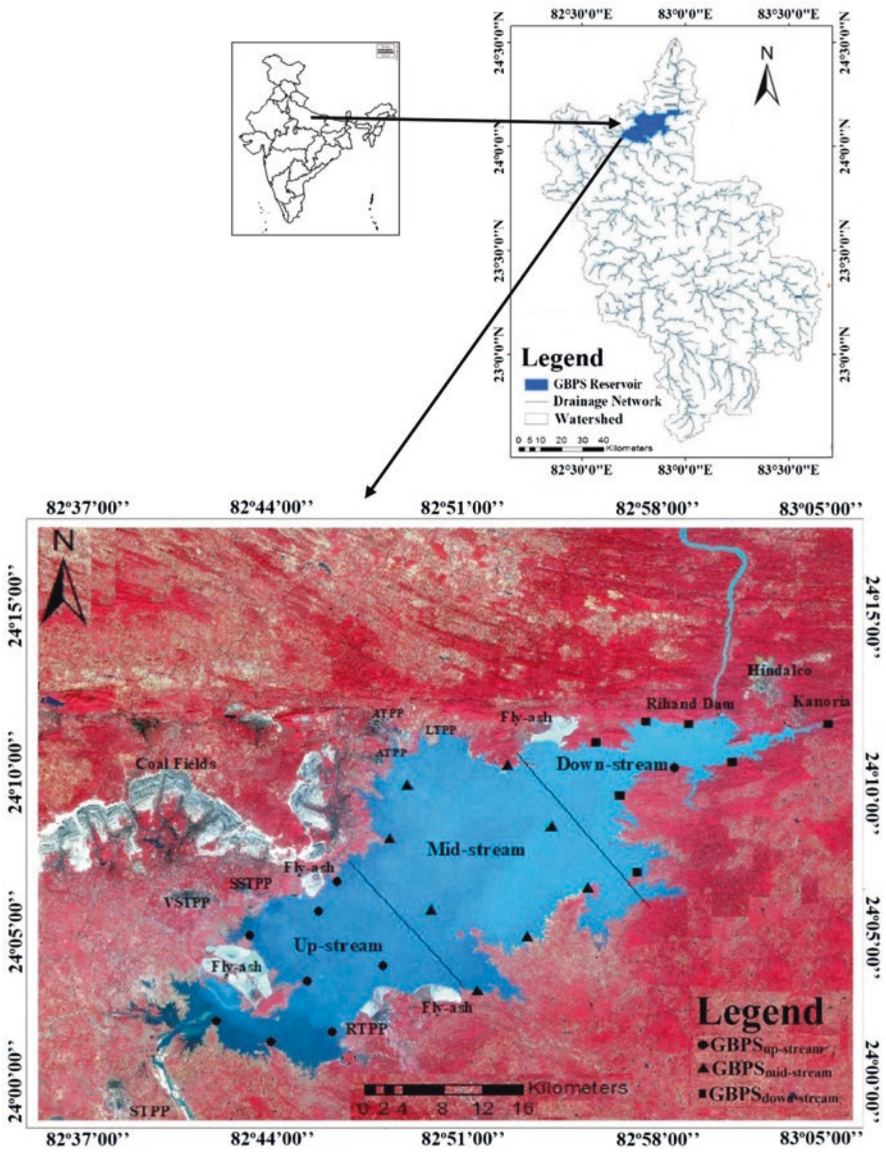

Fig. 7.1 (**a**) Drainage network of Rihand River Basin and (**b**) sampling locations of surface sediments in and around Govind Ballabh Pant Sagar (GBPS) reservoir

spatial dissemination of K/I proportion, Samantaray et al. (2003) recognized four sedimentological zones: (a) the north-western part, demonstrating Gondwana provenance, (b) the southern and eastern parts showing gneissic cause of the silt, (c) the western bank demonstrating root from gneisses, and (d) the mud brought by Rihand waterway into the store showing gneissic provenance of the residue.

7.2.2 Sediment Sampling and Analysis

For the collection of surface sediment samples, GBPS reservoir was divided into three regions to ensure representativeness and variability in the catchments of the GBPS reservoir: (i) $GBPS_{upstream}$ (polluted by industries, urban wastewater, discharge of untreated sewage and fly ash ponds, organic debris, flood plains, soil erosion etc.), (ii) $GBPS_{midstream}$ (polluted by discharge from fly ash ponds and soil erosion), and (iii) $GBPS_{downstream}$ (soil erosion, inflow of rivers and stream passing through forest regions). The total 24 surface sediment samples (0–5 cm), 8 from each region, were collected in the winter season (December 2014) (Fig. 7.1). All the collected samples were stored in a portable ice box at 4 °C. After transport to the laboratory, samples were air-dried at room temperature; stones and plant fragment were removed by passing the dried samples through 2 mm sieve for further experimental analysis. The total content of major and trace elements was measured by ICP-MS. Organic matter (% OM) was measured as weight loss after ignition at 5500C for 6 h (Zhou et al. 2005). The pH and electrical conductivity (EC) of the sediment samples were measured in sediment: water suspension (1:2.5). Sediments were digested by microwave acid digestion for the total phosphorus (Vorland et al. 2017), and the concentrations were determined with the phosphomolybdate blue method (APHA 1998).

7.2.3 Phosphate Adsorption Kinetic Experiments

Air-dried surface sediments samples (2.00 g) treated with two drops of 0.1% chloroform were placed in a series of 250 ml acid-washed conical flasks with 100 ml phosphate solutions (KH_2PO_4, containing 1 mg l^{-1} P) (An and Li 2009). The pH values of the solutions were accustomed by adding 0.01 mol L^{-1} NaOH and 0.01 mol L^{-1} HCl at 7.5–8.2 according to the actual pH of the reservoir. The suspensions were placed in an orbital shaker at 20 ± 1 °C and 200 rpm. Subsequently, 5 ml sample solution was collected from each bottle at 0, 0.25, 0.5, 1, 2, 5, 10, 24, 32, 48, 56, and 72 h and centrifuged immediately at 5000 rpm for 15 min (Zhou et al. 2005). Before phosphate analyses, the solution was filtered through a 0.45 μm GF/C filter membrane. For all samples, triplicates were analyzed, and the data are expressed as the average.

7.2.4 Phosphate Adsorption Isotherm Experiments

Approximately 1.00 g air-dried sediments were put into acid-washed centrifuge tubes (50 ml), and 30 ml phosphate standard solutions (anhydrous KH_2PO_4) of various concentrations (0, 0.05, 0.1, 0.2, 0.3, 0.5 and 0.8) were added. The conditions of the other experiments were the same as those in the adsorption kinetic experiments. After 48 h of equilibration, the solutions were centrifuged at 5000 rpm for 15 min, and the equilibrium phosphate concentrations were analyzed using the ascorbic acid method for phosphorus (APHA 1998). For all samples, triplicates were analyzed, and the data are expressed as the average.

7.3 Results and Discussion

7.3.1 Sediment Characteristics

The physical and chemical characteristics of the surface sediments are shown in Table 7.1. The mean values of pH, EC, and OM were high in surface sediments of the upstream region and differ significantly ($P < 0.05$) among sampling sites. The spatial distribution of Si, Al, and Fe did not differ significantly ($P < 0.05$) among sampling sites. The sedimentary concentrations of Ca, Mg, Na, and K were high in $GBPS_{upstream}$ and showed a significant difference ($P < 0.05$), indicating the impact of the polluted inflow of rivers, streams, and fly ash ponds in GBPS reservoir. The industrial and municipal wastewater, sedimentation of fly ash, livestock waste, and organic debris were major threats to the GBPS reservoir. Other elements were also showing high concentrations in $GBPS_{upstream}$ region and showed a significant difference ($P < 0.05$) among sampling sites. The low concentrations of trace elements in

Table 7.1 Summary of physical and chemical characteristics of the sediments, with the standard error given in parentheses

Parameter(s)	Unit	$GBPS_{upstream}$ (n = 8)	$GBPS_{midstream}$ (n = 8)	$GBPS_{downstream}$ (n = 8)	CV (%)
**pH		8.1 (0.13)	7.9 (0.14)	8.0 (0.10)	4.34
**EC	μS cm^{-1}	908.7 (71.02)	899.3 (51.83)	875.9 (99.94)	23.56
*OM	%	4.5 (0.59)	4.0 (0.47)	2.6 (0.23)	31.83
**Si		28.1 (2.73)	30.6 (2.60)	29.3 (3.14)	27.28
*K		3.4 (0.33)	2.4 (0.39)	1.5 (0.34)	46.11
**Al		2.5 (0.27)	2.8 (0.25)	2.6 (0.28)	29.29
**Fe		1.9 (0.22)	1.7 (0.26)	1.4 (0.26)	41.40
*Ca		1.3 (0.31)	0.9 (0.16)	0.3 (0.07)	59.98
*Na		1.1 (0.20)	0.7 (0.15)	0.3 (0.12)	66.18
*Mg		0.3 (0.06)	0.1 (0.02)	0.1 (0.03)	58.63
*Mn	mg kg^{-1}	477.0 (53.76)	344.5 (31.26)	245.3 (50.88)	38.73
*Zr		84.1 (5.86)	63.8 (11.45)	37.3 (13.80)	40.47
*Cr		52.8 (9.19)	33.3 (5.39)	27.3 (4.19)	46.09
*V		46.8 (3.62)	38.0 (4.71)	27.8 (4.62)	34.68
*Zn		45.9 (6.14)	30.1 (2.67)	23.0 (7.17)	50.36
*Cu		44.9 (9.89)	31.5 (3.51)	20.5 (2.54)	42.98
*Sr		43.38 (9.10)	30.75 (4.10)	20.38 (2.39)	43.43
*Ni		14 (3.42)	9.44 (1.53)	2.98 (0.97)	69.05
*Co		7.46 (1.01)	5.98 (0.93)	3.28 (0.81)	50.64
**TP		215.14 (16.87)	202.72 (16.22)	186.94 (20.67)	25.36

*indicates parameter is significantly variable across sampling regions at $p < 0.05$
**indicates parameter is nonsignificantly variable across sampling regions at $p < 0.05$

$GBPS_{midstream}$ and $GBPS_{downstream}$ regions may be due to the dilution of pollution load contributed by $GBPS_{upstream}$ region, and quality of sediments deposited by inflow rivers and streams were different than $GBPS_{upstream}$ region. The mean of total P concentrations was high in surface sediments of $GBPS_{upstream}$ than the $GBPS_{midstream}$ and $GBPS_{downstream}$ regions and showed the nonsignificant difference ($P < 0.05$) among sampling sites.

7.3.2 Phosphate Adsorption Kinetics

The phosphate adsorption kinetics showed an initial fast sorption step, completed within 10 h, and followed by a slower second stage, completed within 48 h (Fig. 7.2). The amount of adsorbed phosphorus on the sediment after 24 h was taken to represent a pseudo-equilibrium condition. The experimental data revealed that the adsorption process reached equilibrium after 48 h. After 10 h, 71.10%, 72.31%, and 67.80% of phosphate were adsorbed in surface sediments of upstream, midstream, and downstream equilibrium stages, respectively. This showed highly polluted surface sediments of $GBPS_{upstream}$ than $GBPS_{midstream}$ and $GBPS_{downstream}$ regions. The adsorption of phosphate onto sediments has been widely reported as multiple kinetic processes involving at least two steps at different rates: a fast initial reaction and a slow step reaction (Lopez et al. 1996; Jalali and Peikam 2013). In the present study,

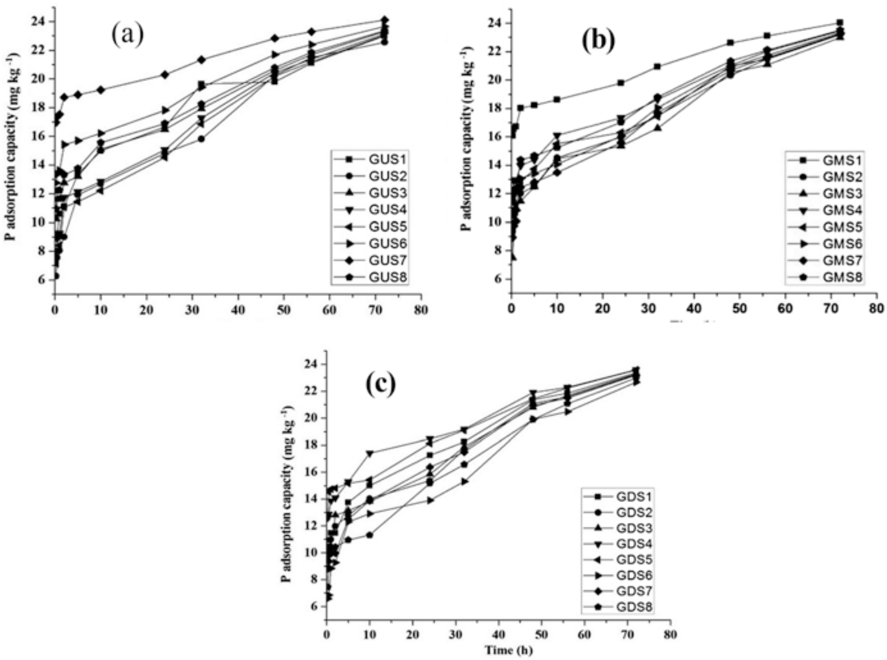

Fig. 7.2 The phosphate sorption kinetics of surface sediments (**a**) $GBPS_{upstream}$ (**b**) $GBPS_{midstream}$, and (**c**) $GBPS_{downstream}$

wide spatial variations were found in adsorption capacity of surface sediments collected from three different regions of the GBPS reservoir.

In order to investigate the mechanism of adsorption and potential rate controlling steps, the pseudo-first-order rate equation (Eq. 7.1) and pseudo-second-order rate equation (Eq. 7.2) were used:

$$\ln\left(Qe - Q\right) = \ln Qe - k_1 t \tag{7.1}$$

$$t / Q = 1 / k_2 Qe^2 + t / Qe \tag{7.2}$$

where Q (mg kg^{-1}) is the amount of adsorbed phosphorus on the sediment at time t (h), Qe (mg kg^{-1}) is Q at equilibrium status, and k_1 (h^{-1}) and k_2 (kg mg^{-1} h^{-1}) are the rate constants of the first-order adsorption and second-order adsorption, respectively.

The values of constants (k_1 and k_2), Qe, and correlation coefficients (R^2) of Eqs. (7.1 and 7.2) are given in Table 7.2. The pseudo-second-order rate model described the kinetics of P adsorption with a high correlation coefficients (R^2 = 0.97–0.99), (R^2 = 0.98–0.99), and (R^2 = 0.96–0.99) for surface sediments of $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$, respectively, than that of pseudo-first-order rate equation. This recommends that the rate-limiting step may be chemical sorption involving valency forces through sharing or exchange of electrons between anions and absorbent, which provides the best correlation of the data (Song et al. 2017). The change of rate constant due to the concentration and time shows that the absorption is chemically rate controlled.

After 10 h, the values of P adsorption capacity varied from 12.2 to 19.2 mg kg^{-1}, 13.5 to 18.6 mg kg^{-1}, and 11.3 to 17.4 mg kg^{-1} in $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$, respectively. In this study, the values of P adsorption capacity were less than other global studies (Tian and Zhou 2007; Cui et al. 2017). This might be possible due to coarse texture of the sediments (Anshumali and Ramanathan 2007), low availability of sorption sites, and Ca and P concentrations (Yagi and Fukushi 2012). The sorption rate is used to describe the phosphate sorption by the sediments (Liu et al. 2002). The sorption rate with time is shown in Table 7.3. The sorption rates of 0–0.25 h were the highest over 48 h, ranging from 25.06 to 67.87 mg $kg^{-1}h^{-1}$ (mean = 40.79 mg $kg^{-1}h^{-1}$), 29.95 to 64.30 mg $kg^{-1}h^{-1}$ (mean = 41.98 mg $kg^{-1}h^{-1}$), and 26.32 to 50.83 mg $kg^{-1}h^{-1}$ (mean = 38.88 mg $kg^{-1}h^{-1}$) in $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$, respectively. This suggests that a quick sorption process occurred within 0.25 h in the GBPS catchment. However, the sorption rates for sediments of GBPS reservoir are less than other global studies. An and Li (2009) reported 7.25–282.92 mg $kg^{-1}h^{-1}$ sorption rates for sediments of Nansi Lake in China.

7.3.3 Sorption Isotherm of Phosphate

The sorption isotherm experiments were carried out to calculate the sorption capacity of P by surface sediments using Langmuir sorption model (Langmuir 1948; Tian and Zhou 2007):

Table 7.2 Adsorption kinetic parameters of pseudo-first- and pseudo-second-order rate reaction

Sampling area		First-order kinetics			Second-order kinetics		
		K_1 (h^{-1})	Q_e (mg kg^{-1})	R^2	K_2 (kg mg^{-1} h^{-1}	Q_e (mg kg^{-1})	R^2
$GBPS_{upstream}$	GUS1	0.0052	11.08	0.83	0.38	16.67	0.99
	GUS2	0.0069	8.72	0.83	0.94	14.83	0.97
	GUS3	0.0045	12.06	0.91	0.441	16.48	0.98
	GUS4	0.0058	10.07	0.88	0.76	15.06	0.97
	GUS5	0.0064	9.28	0.87	0.93	14.54	0.97
	GUS6	0.0035	14.21	0.91	0.25	17.82	0.99
	GUS7	0.0020	17.91	0.93	0.07	20.29	0.99
	GUS8	0.0042	12.67	0.91	0.37	16.88	0.99
$GBPS_{midstream}$	GMS1	0.0023	17.13	0.93	0.10	19.77	0.99
	GMS2	0.005	11.3	0.91	0.54	15.98	0.98
	GMS3	0.0054	10.59	0.83	0.62	15.34	0.98
	GMS4	0.0039	13.35	0.92	0.31	17.33	0.99
	GMS5	0.0045	12.04	0.85	0.42	16.31	0.98
	GMS6	0.0049	11.57	0.90	0.51	16.06	0.98
	GMS7	0.0053	10.86	0.89	0.62	15.59	0.98
	GMS8	0.0041	13.02	0.91	0.35	17.03	0.99
$GBPS_{dowstream}$	GDS1	0.0048	11.87	0.90	0.42	17.24	0.99
	GDS2	0.0050	11.29	0.93	0.59	15.38	0.98
	GDS3	0.0051	11.25	0.89	0.56	15.85	0.98
	GDS4	0.0036	14.05	0.89	0.22	18.46	0.99
	GDS5	0.0034	14.34	0.94	0.27	18.12	0.99
	GDS6	0.0066	8.83	0.83	0.99	13.89	0.96
	GDS7	0.0057	10.41	0.89	0.61	16.38	0.98
	GDS8	0.0056	9.81	0.91	0.95	15.17	0.97

Table 7.3 Phosphate sorption rate on the sediments at different sampling intervals (mg kg^{-1} h^{-1})

Surveyed area		Sampling intervals (h)								
		0–0.25	0.25–0.5	0.5–1	1–2	2–5	5–10	10–24	24–32	32–48
GBPSupstream	GUS1	36.92	18.48	10.58	5.56	2.67	1.50	0.69	0.61	0.41
	GUS2	25.06	15.11	8.05	4.50	2.39	1.27	0.62	0.49	0.42
	GUS3	40.97	23.19	11.60	6.37	2.64	1.51	0.69	0.56	0.43
	GUS4	32.17	17.79	9.24	5.87	2.42	1.28	0.63	0.54	0.43
	GUS5	28.60	16.10	8.41	5.52	2.29	1.22	0.61	0.53	0.42
	GUS6	51.00	26.73	13.62	7.71	3.14	1.62	0.74	0.61	0.45
	GUS7	67.87	34.74	17.54	9.36	3.78	1.92	0.85	0.67	0.48
	GUS8	43.75	24.45	12.23	6.66	2.75	1.56	0.70	0.57	0.43
GBPSmidstream	GMS1	64.30	33.05	16.71	9.01	3.64	1.86	0.82	0.65	0.47
	GMS2	37.50	21.61	10.82	6.01	2.50	1.45	0.67	0.55	0.42
	GMS3	29.95	19.66	10.99	5.73	2.50	1.44	0.64	0.52	0.43
	GMS4	46.87	25.87	12.94	6.99	2.87	1.61	0.72	0.58	0.44
	GMS5	36.96	22.69	12.39	6.40	2.75	1.55	0.68	0.54	0.44
	GMS6	38.96	21.01	10.82	6.53	2.68	1.41	0.67	0.56	0.44
	GMS7	35.74	19.49	10.07	6.22	2.56	1.35	0.65	0.55	0.43
	GMS8	45.56	24.15	12.35	7.18	2.93	1.52	0.71	0.59	0.44
GBPSdownstream	GDS1	41.76	21.87	11.45	5.74	2.75	1.50	0.72	0.57	0.44
	GDS2	39.03	20.88	10.99	5.99	2.56	1.40	0.64	0.55	0.44
	GDS3	37.53	20.33	10.49	6.39	2.63	1.38	0.66	0.56	0.43
	GDS4	50.50	25.71	13.87	7.04	3.06	1.74	0.77	0.60	0.46
	GDS5	50.83	29.07	14.74	7.40	3.03	1.54	0.76	0.60	0.45
	GDS6	26.32	13.72	8.84	4.63	2.46	1.29	0.58	0.48	0.42
	GDS7	35.29	18.74	9.95	4.98	2.50	1.39	0.68	0.55	0.44
	GDS8	29.76	20.10	10.34	5.22	2.19	1.13	0.63	0.52	0.41

Table 7.4 Summary of Langmuir isotherm parameters, with the standard error given in parentheses

Parameters	GBPSupstream (n = 8)	GBPSmidstream (n = 8)	GBPSdownstream (n = 8)
m (L kg^{-1})	33.15 (2.68)	33.27 (2.21)	32.92 (1.11)
WNAP (mg kg^{-1})	2.89 (0.64)	4.01 (1.21)	4.80 (0.98)
R^2	0.98 (0.01)	0.97 (0.01)	0.98 (0.003)

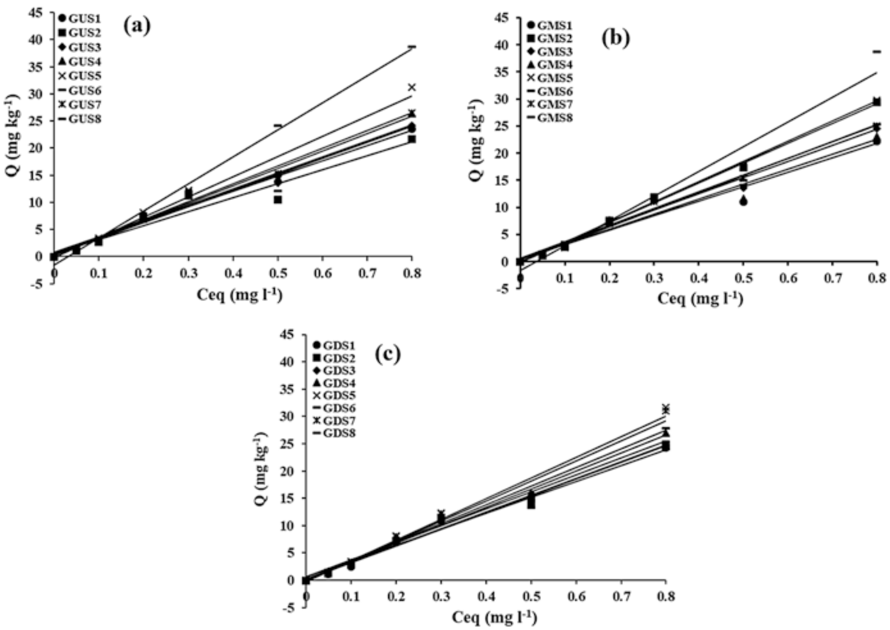

Fig. 7.3 Phosphorus adsorption isotherm of surface sediments (**a**) $GBPS_{upstream}$ (**b**) $GBPS_{midstream}$ and (**c**) $GBPS_{downstream}$

$$Q = mC_{eq} - W_{NAP} \tag{7.3}$$

where Q is the adsorbed phosphorus from the standard phosphate solution, C_{eq} is the equilibrium concentration of phosphorus in solution (0–0.8 mg l^{-1}), m is the slope, and W_{NAP} is the content of native adsorbed phosphorus (NAP, mg kg^{-1}).

The results of the sorption isotherm parameter are given in Table 7.4. The C_{eq} versus Q presented a good fit to the Langmuir model in $GBPS_{upstream}$ ($R^2 \geq 0.94$), $GBPS_{midstream}$ ($R^2 \geq 0.95$), and $GBPS_{downstream}$ ($R^2 \geq 0.97$) (Fig. 7.3). The mean values of W_{NAP} were 2.89 mg kg^{-1}, 4.01 mg kg^{-1}, and 4.80 mg kg^{-1} in GBPSupstream, GBPSmidstream, and GBPSdownstream regions, respectively; the slope values were 33.15, 33.27, and 32.92 L kg^{-1} in $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$ regions, respectively.

In this study, the Langmuir model showed a linear relationship between adsorbed phosphorus (Q) and the equilibrium concentration of phosphorus in solution (C_{eq}). This may be possible due to the low concentration of adsorbed phosphate and coarse texture of polluted surface sediments (Han et al. 2011). Nevertheless, the W_{NAP} values were 1.3–1.6 times greater in $GBPS_{upstream}$ than the $GBPS_{midstream}$ and $GBPS_{downstream}$. These could be attributed to terrigenous phosphorus input from the south-western region of the $GBPS_{upstream}$ and its bank. The south-western region of GBPS reservoir was polluted by Ballia Nala and Kachan River, carrying a large amount of coal mine and thermal power plant effluent and sewage flow into GBPS reservoir (Anshumali et al. 2014).

When the phosphorus desorption quantity equivalents the quantity of phosphorus adsorption in the experimental (Q = 0), the concentration of phosphorus in the solution is called adsorption equilibrium concentration (C_{EPC}) (Dittrich et al. 2013). C_{EPC} is an significant parameter to measure and provide convenient information about whether sediments will release or adsorb dissolved phosphorus when placed in contact with water (Han et al. 2011). The C_{EPC} was calculated by Eq. (7.4):

$$C_{EPC} = W_{NAP} / m \tag{7.4}$$

Mean C_{EPC} were 0.09 mg l^{-1}, 0.12 mg l^{-1}, and 0.15 mg l^{-1} in the $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$, respectively (Table 7.5). These values were less than C_{eq} indicating that the surface sediments would adsorb NAP from overlying water as a sink in the GBPS reservoir. This is further supported by a positive relationship between W_{NAP} and C_{EPC} (Table 7.5).

The amount of phosphorus adsorbed on the surface sediments is the maximum adsorption ($Q_{max,}$ mg kg^{-1}) with a phosphorus concentration of 0.80 mg L^{-1}. For GBPS reservoir, the Q_{max} varied from 26.96 mg kg^{-1} to 27.26 mg kg^{-1} to

Table 7.5 Summary of adsorption isotherm parameters and their relationship, with the standard error given in parentheses

Parameters	GBPSupstream (n = 8)	GBPSmidstream (n = 8)	GBPSdownstream (n = 8)
CEPC (mg l^{-1})	0.09 (0.02)	0.12 (0.04)	0.15 (0.03)
Kp (L kg^{-1})	34.53 (4.37)	35.20 (4.12)	32.98 (1.08)
Q_{max} (mg kg^{-1})	26.96 (1.97)	27.27 (1.90)	26.93 (1.07)
TQmax (mg kg^{-1})	29.86 (1.98)	31.27 (2.14)	31.73 (1.45)
WNAP vs TQmax	y = 0.5427x + 28.286 R^2 = 0.0306	y = 0.7957x + 28.083 R^2 = 0.2313	y = 1.0004x + 26.93 R^2 = 0.4587
WNAP vs. CEPC	y = 0.0297x−0.0051 R^2 = 0.9675	y = 0.0302x + 0.0015 R^2 = 0.9829	y = 0.0319x−0.0067 R^2 = 0.9823
Kp vs Qmax	y = 0.4348x + 11.948 R^2 = 0.9285	y = 0.4528 x + 11.328 R^2 = 0.9687	y = 0.8814x−2.1341 R^2 = 0.8022
K_p vs TQ_{max}	y = 0.3922x + 16.315 R^2 = 0.7485	y = 0.3927x + 17.449 R^2 = 0.5713	y = 0.886x + 2.5116 R^2 = 0.4387

26.93 mg kg^{-1} in the $GBPS_{upstream}$, $GBPS_{midstream}$, and $GBPS_{downstream}$, respectively. For the polluted surface sediments, the total amount of phosphorus adsorbed on the surface sediment should include W_{NAP} and Q_{max} (TQ_{max} (mg kg^{-1}) = Q_{max} + W_{NAP}) (Zhou et al., 2005). The mean value of TQ_{max} varied as 29.86 mg kg^{-1}, 31.27 mg kg^{-1}, and 31.73 mg kg^{-1} in the GBPSupstream, GBPSmidstream, and GBPSdownstream, respectively. The positive relationship was observed between W_{NAP} and TQ_{max} only for the $GBPS_{downstream}$ region. The partitioning coefficient ($K_p = W_{NAP}/C_{EPC}$) reflects the relative affinities of surface sediments and overlying water for phosphorus (Zhou et al. 2005). In this study, the mean value of K_p was 34.53 L kg^{-1}, 35.20 L kg^{-1}, and 32.98 L kg^{-1} in GBPSupstream, GBPSmidstream, and GBPSdownstream, respectively (Table 7.5). The similar values of K_p indicated the better ability of surface sediments to adsorb and retain phosphorus in the GBPS reservoir. This is further supported by the positive relationship between K_p and Q_{max} across three sampling regions of GBPS reservoir (Table 7.5).

7.4 Conclusions

The high concentrations of heavy metals occurred in sediments of $GBPS_{upstream}$. This may be due to coal-based industries discharging heavy metals in GBPS reservoir. The sorption isotherms presented a high adsorption capacity ($C_{eq} \geq C_{EPC}$). The C_{EPC} values were less than C_{eq} indicating that the surface sediments would adsorb NAP from overlying water as a sink in the GBPS reservoir. The K_p values and the positive statistical relationship between K_p and Q_{max} indicated the ability of surface sediments to adsorb and retain phosphorus in GBPS reservoir. Further, the investigation is needed to understand the impact of phosphorus enrichment on the diversity of aquatic species and other environmental consequences for sustainable development and management of GBPS reservoir.

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8 Spatiotemporal Variations of Precipitation and Temperatures Under CORDEX Climate Change Projections: A Case Study of Krishna River Basin, India

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Abstract

The Earth's climate is not static; it changes according to the natural and anthropogenic climate variability. Anthropogenic forcing due to increase of greenhouse gases in the atmosphere has driven changes in climate variables globally. Changes in climatological variables have severe impact on global hydrological cycle affecting the severity and occurrence of natural hazards such as floods and droughts. Estimation of projections under climate signals with statistical and dynamic downscaling models and integration with water resource management models for the impact assessment have gained much attention. The fine-resolution climate change predictions of dynamic regional climate model (RCM) outputs, which include regional parameterization, have been widely applied in the hydrological impact assessment studies. Advancement of the Coordinated Regional Downscaling Experiment (CORDEX) program has enabled the use of RCMs in regional impact assessment which has progressed in recent years. CORDEX model outputs were considered to be valuable in terms of establishing large ensembles of climate projections based on regional climate downscaling all over the world. However, the simulations of RCM outputs have to be evaluated to check the reliability in reproducing the observed climate variability over a region. The present study demonstrates the use of bias-corrected CORDEX model simulation in analyzing the regional-scale climatology at river basin scale, Krishna river basin (KRB), India. The precipitation and temperature simulations from CORDEX models with RCP 4.5 were evaluated for the historical data for the period of 1965 to 2014 with India Meteorological Department (IMD) gridded rainfall and temperature data sets cropped over the basin. The projected increase

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of precipitation under climate signals was predicted to be from 74.4 to 136.7 mm over KRB for the future time period of 2041–2060 compared to the observed periods of 1966–2003. About 1.06 °C to 1.35 °C of increase in temperatures was predicted for the periods of 2021–2040 and 2041–2060, respectively, compared to the observed period of 1966–2014 over KRB. The climate variable projections obtained based on RCM outputs can provide insights toward the variations of water-energy variables and consequent impact on basin yields and losses in river basin management.

Keywords
Bias correction · Dynamic downscaling · Hydrology · Regional circulation model (RCM) · General circulation model (GCM)

8.1 Introduction

The totality of atmosphere, hydrosphere, biosphere, and geosphere and their interactions are referred as climate system (Mcguffie and Henderson-Sellers 1997). The Earth's climate is not static; it changes in response to natural and anthropogenic climate forcing. Climate change refers to climatic conditions over a period of time ranging from months to thousands or millions of years. The standard period is defined as 30 years according to the World Meteorological Organization (WMO). Apart from anthropogenic emission of greenhouse gases, which is considered as external forcing, internal forcing such as volcanic eruption and solar variation determines the dynamics of climate system (IPCC 2007). In this context, increasing temperatures and changes in precipitation patterns have been observed all over the world (Hansen et al. 2010) under anthropogenic climate change. The consequent and immediate impact of climate change is on intensification of global hydrological cycle leading to increase of intensity and frequency of climate hazards such as droughts, floods (Rosenzweig et al. 2010), heat and cold waves, etc. The most significant impact of climate change is anticipated to be on regional water-energy variables of hydrological cycle, thus affecting water supply and demand (Cunderlik and Simonovic 2005). The increasing concern of climate change and its impacts on hydrological variables have motivated several researchers to estimate the projected climatological variables accounting for greenhouse gases in the atmosphere (Ghosh and Mujumdar 2008). In this context, prediction of accurate projections of hydroclimatological variables under climate change is crucial for making adaptive measures and mitigation policies (IPCC 2007). To this end, climate change impact assessment studies have been advanced due to the availability of general circulation models (GCMs) as the most credible tools for investigating the physical processes of the earth surface-atmosphere system. The GCMs can simulate the projections of climatological variables for current as well as for future scenarios accounting for greenhouse gas emission scenarios. These are the numerical models, which analyze the atmosphere on an hourly basis in all three dimensions based on the law of conservation of energy, mass, momentum, and water vapor and ideal gas law (Mcguffie and Henderson-Sellers 1997). These are complex computer simulations describing the circulation of air and ocean currents and how the energy is transported within a climate system. GCMs are classified as atmospheric general circulation models (AGCM) or oceanic general circulation models (OGCM) for modeling atmospheric and oceanic circulations (Mcguffie and Henderson-Sellers 1997). Most of the climate change impact assessment studies mainly focus on the use of GCM outputs of various climatological variables and their integration with hydrological modeling (Rehana and Mujumdar 2014; Teutschbein et al. 2011; Chen et al. 2011).

The Intergovernmental Panel on Climate Change (IPCC) has been established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to provide scientific, technical, and socioeconomic information for understanding the climate change process. The IPCC provides scientific information to the research community in terms of future possible climate change scenarios for policy- and decision-making (IPCC 2007, 2014). The IPCC has developed long-term emission scenarios based on the radiative forcing and demographic, technical, and socioeconomic information, which are considered a standard reference to be followed for the policymakers, scientists, and other experts. Such emission scenarios enabled the scientific community to carry out climate change analysis, modeling, impact assessment, adaptation, and mitigation studies. Based on the Assessment Report 4 (AR4), IPCC has defined Special Report on Emission Scenarios (SRES) of four storylines as A1, B1, A2, and B2 determined by driving forces such as demographic development, socioeconomic development, and technology change along with CO_2 level changes (IPCC 2007) (https://www.ipcc.ch/assessment-report/ar4/). Whereas the IPCC Assessment Report 5 (IPCC 2014) has replaced the SRES of AR4 with Representative Concentration Pathways (RCPs) RCP8.5, RCP6, RCP4.5, and RCP2.6, here, the RCPs refer to time-dependent projections of atmospheric greenhouse gas concentrations (https://www.skepticalscience.com/rcp.php), and the numbers 8.5, 6, 4.5, and 2 represent the radiative forcing, expressed as Watts/m^2. For example, RCP 8.5 is high pathway for which radiative forcing reaches >8.5 Watts/m^2 by 2100 and continues to rise. The RCP 6 and 4.5 are considered to be stabilization pathways, while for RCP 2 the radiative forcing peaks at approximately 3 Watts/m^2 before 2100 and then declines. Integration of projected climatological variables under climate change scenarios with water resource decision and management models to study the impact assessment over water quantitative and qualitative availabilities and demands has widely gained much attention in the research community (Ghosh and Mujumdar 2008; Raje and Mujumdar 2010; Rehana and Mujumdar 2014; Mishra et al. 2014).

Assessment of climate change impacts on water resources necessitates accurate projections of various hydroclimate variables, which involves downscaling the projections of climate variables to hydrological variables. It is of growing importance to create accurate projections of hydrometeorological variables by employing climate model outputs with general circulation models (GCMs) and regional circulation models (RCMs) which can then be statistically or dynamically downscaled (Fowler et al. 2007). To obtain the projections of hydrometeorological variables (precipitation, runoff, temperature, etc.) at regional scales based on large-scale climate simulations (mean sea level pressure, wind speed, humidity, etc.) obtained from GCMs, downscaling models have been advanced (Hewitson and Crane 1992; Wilby et al. 2004; Tripathi et al. 2006; Anandhi et al. 2008; Rehana and Mujumdar 2012). Broadly, the downscaling techniques are classified as dynamic and statistical downscaling models. The statistical downscaling model involves deriving empirical relationships between large-scale climate variable simulations (predictors) obtained from GCMs and regional-scale hydroclimatological variables (predictands) (Wilby et al. 2004). The spatial resolution of statistical downscaling projections depends on the scale of the regional hydrological variables, and also the spatial resolution of GCMs is generally coarse ranging from 2.8°×2.8° to 1.1°×1.1°.

The dynamic downscaling uses a nested higher-resolution regional climate model (RCM) within a coarse resolution GCM. The RCMs work at finer resolution and provides better dynamic downscaling climate change predictions for a particular region (Buontempo et al. 2015) with region-specific parameterization (Singh et al. 2017). The use of RCMs for impact assessment should be based on the evaluation of the climate projections with observed data given the debate on the use of RCM projections directly (Racherla et al. 2012; Feser et al. 2011). Due to the fine-resolution climate model, projections of RCMs, which enable to synthesize the climate change prediction, and hydrological models to study the regional impact assessment studies became widely applicable (Das and Umamahesh 2018). Further, RCMs provide dynamically downscaled GCM outputs at fine resolutions compared to coarser statistical downscaled outputs, which can be directly used in the impact assessment studies (Sun et al. 2006) by testing their performance with current climate (Singh et al. 2017). The recent regional climate model is available through Coordinated Regional Climate Downscaling Experiment (CORDEX), is mainly associated with GCM projections from Coupled Model Intercomparison Project (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/), was downscaled with the RCMs run by various research institutes, and is available for 14 domains covering the entire globe. The present study provides an emphasis to incorporate such CORDEX projections of precipitation and temperatures to study the regional climate change impacts at river basin scales. The Krishna river basin, India, was considered as case study to study the regional climate-induced changes of precipitation and temperatures with various CORDEX model outputs.

8.2 Data and Methods

The Krishna river basin (KRB) is the fifth largest river system of India and occupies an area of 2, 58, 948 km^2 which is 8% of the total geographical area of the country. Nearly 44% of KRB lies in Karnataka, 26% in Maharashtra, about 15% in Telangana, and another 15% in Andhra Pradesh within the range 73°17'–81°9'E and 13°10'–19°22' N (Fig. 8.1). The major tributaries of the river are Ghataprabha, Malaprabha, Tunga-Bhadra, Bhima, Vedavathi, and Musi. The annual average precipitation in the basin is 784 mm, of which approximately 90% occurs during

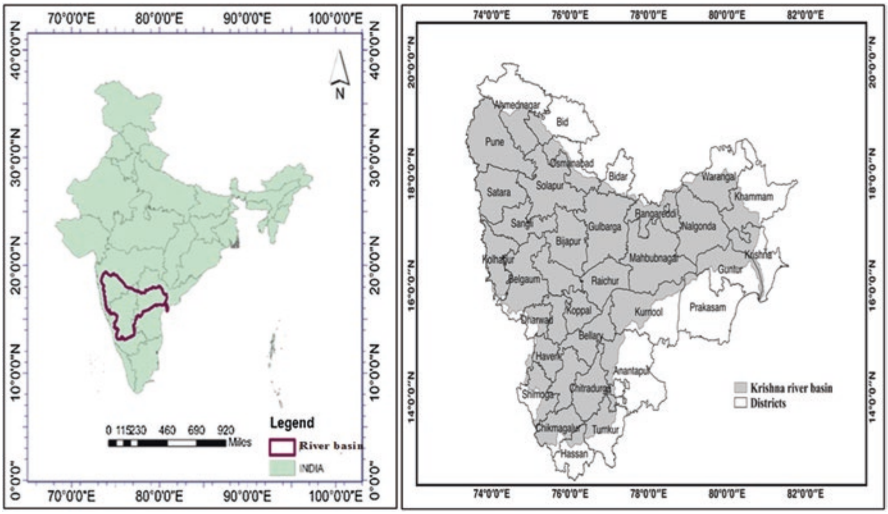

Fig. 8.1 Map for the Krishna river basin (**a**) Location of the catchment in India (**b**) Krishna basin and districts map

the southwest monsoon from June to October (http://india-wris.nrsc.gov.in/wrpinfo/?title=Krishna). The study used gridded daily precipitation data from the India Meteorological Department (IMD) available for the period of 1901 to 2015 at 0.25° × 0.25° resolution (Rajeevan and Bhate 2009). The gridded daily average temperature data all over India at a resolution of 1° × 1° for the period of 1951–2014 from IMD was cropped to the basin (Srivastava et al. 2009). The temperature was interpolated to 0.25° × 0.25° resolution using the inverse distance weighting method from 1° X 1° resolution. The CORDEX (Coordinated Regional Downscaling Experiment) is mainly associated with GCM projections from Coupled Model Intercomparison Project (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/) and was downscaled with the RCMs run by various research institutes. CORDEX data sets are available for 14 domains covering the entire globe, and the present study selected South-Asian domain of the CORDEX project from Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India (http://cccr.tropmet.res.in/home/index.jsp). Daily precipitation and temperature data simulated by 3 RCMs, driven by various GCMs, were obtained from the CORDEX (www.cordex.org). Three CORDEX experiments: (1) RegCM4(LMDZ), the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4; Giorgi et al. 2012), with deriving GCM as IPSL LMDZ4, from Laboratoire de M'et'eorologie Dynamique (France), India; (2) CCLM4(MPI), COnsortium for Small-scale MOdelling (COSMO) model in Climate Mode version 4.8 (CCLM; Dobler and Ahrens 2008), with deriving GCM as Max Planck Institute for Meteorology, Germany, Earth System Model (MPI-ESM-LR; Giorgetta et al. 2013), from Institute for Atmospheric and Environmental Sciences (IAES), Goethe University, Frankfurt am Main (GUF), Germany; and

(3) REMO2009 (MPI) regional model, with deriving GCM as MPI-ESM-LR (Giorgetta et al. 2013), from Climate Service Center, Hamburg, Germany. The projections for the period of 2006 to 2060 were analyzed under the Representative Concentration Pathway (RCP) 4.5 representing atmospheric radiation at 4.5 W m^{-2} at the end of 2100.

The RCM outputs are generally associated with systematic biases in the simulated projections compared to real observations (Buontempo et al. 2015). The regional climate model simulations are burdened with systematic bias resulting from inadequate physics and bias in GCM simulations used in the boundary conditions affecting the historical and future projections (Ehret 2012). Therefore, the present study adopted quantile-based mapping method developed by Li et al. (2010) with the comparison of cumulative distribution functions (CDFs) of observed and RCM simulated data of precipitation and temperatures for the historical and future scenarios. Here, the CDFs of RCM and IMD gridded data sets of precipitation, and temperatures were compared to correct the bias present in RCM historical and future data sets (Li et al. 2010), where Gamma distribution is used to calculate the CDFs of each time series as follows:

$$X_{m-p.adjst} = F_{o-c}^{-1}\left(F_{m-c}\left(x_{m-p}\right)\right) \tag{8.1}$$

where

$X_{m-p.adjst}$ is the bias-corrected climate variable for current period (RCM-historical)
x_{m-p} = biased RCM variable
F_{m-c} = CDF of RCM Historical data
F_{o-c} = CDF of IMD (Observed) data and F_{o-c}^{-1} is the inverse CDF of IMD data, which gives the observed variable at the corresponding equal CDF level

For bias correction of future RCM data, it is generally assumed that the difference between the model and observed value during the training period also applies to the future period, for a given percentile, which means the adjustment function remains the same. However, the difference or shift between the CDFs for the future and historic periods is also taken into account;

$$X'_{m-p.adjst} = x_{m-p} + \boldsymbol{F}_{o-c}^{-1}\left(\boldsymbol{F}_{m-p}\left(\boldsymbol{x}_{m-p}\right)\right) - \underbrace{\boldsymbol{F}_{m-c}^{-1}\left(\boldsymbol{F}_{m-p}\left(\boldsymbol{x}_{m-p}\right)\right)}_{\text{RCM Shift}} \tag{8.2}$$

where

$X'_{m-p.adjst}$ is the bias-corrected climate variable for future period (RCM-future)
x_{m-p} = biased RCM future variable
F_{m-p} = CDF of RCM Future data
F_{o-c} = CDF of IMD (Observed) data
F_{o-c}^{-1} = inverse CDF of IMD data which gives the IMD variable at the corresponding equal CDF level

F_{m-c} = CDF of RCM historical data
F_{m-c}^{-1} = inverse CDF of RCM data which gives the RCM variable at the corresponding equal CDF level

The RCM data sets which are at a resolution of 0.44° × 0.44° were brought to the IMD precipitation data resolution of 0.25° × 0.25° using the inverse distance weighting method after bias correction. The Krishna river basin has shown significant changes after 2003 with spatially averaged precipitation increase of about 28 mm/decade with Pettitt change point detection year as 2003. Therefore, to study the basin-averaged changes of precipitation and temperatures for current and future climate signals, the present study considered two-time intervals of 1966–2003 and 2004–2014. The precipitation and temperatures were analyzed for the time periods of 1966–2003, 2004– 2014, 2021– 2040, and 2041– 2060 with RCP 4.5 over KRB.

8.3 Results and Discussions

The spatial averaged monthly variation of precipitation and temperatures for the period of 1951 to 2014 is shown in Fig. 8.2, with rainfall contributing months as June to October, whereas the dry months as March, April, and May. To examine the spatial variation of precipitation, the annual average precipitations for three time periods of 1951–1972, 1973–1992, and 1993–2014 were studied as shown in Fig. 8.3(a). The average annual precipitation over KRB was estimated at 975 mm, varying between 650 and 1843 mm. The total annual precipitation amount varied from high toward the Western Ghats boundary of the KRB to low toward East of the

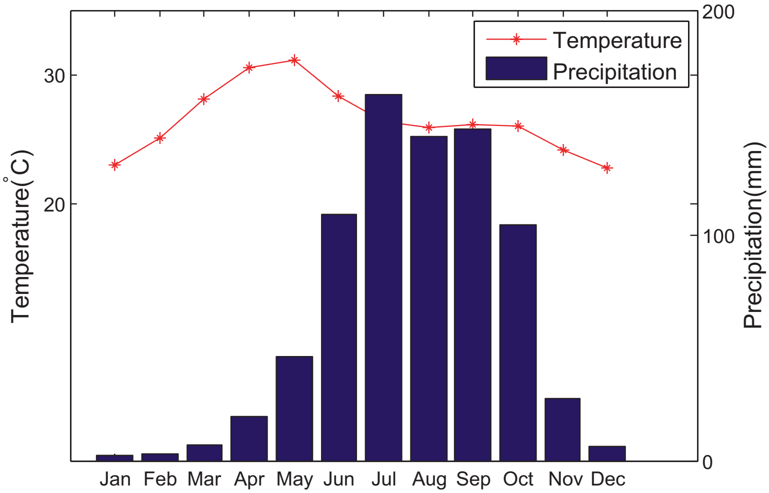

Fig. 8.2 The spatial average monthly average temperature and precipitation over Krishna river basin for 1951–2014

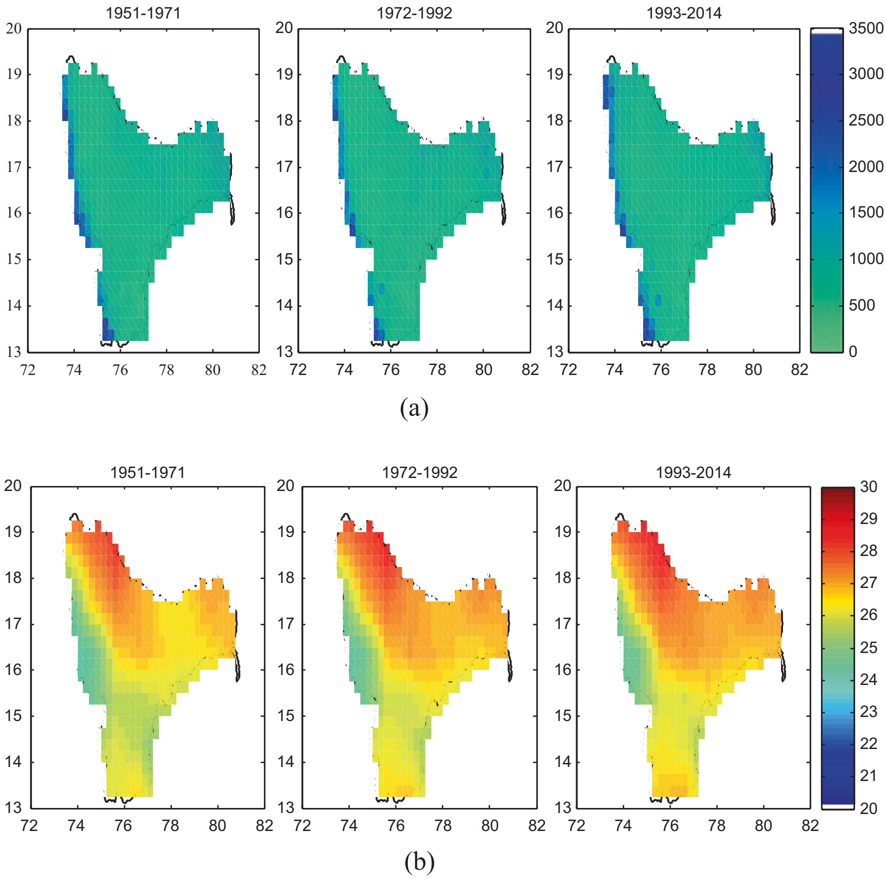

Fig. 8.3 Spatial variation in annual total (**a**) precipitation in mm (**b**) temperature in °C for 1951–1971, 1972–1992, and 1993–2014

basin, covering few districts of Telangana. Figure 8.4 (a) shows the temporal trends of basin-averaged precipitation for the period of 1965–2014. The basin-averaged annual average precipitation has shown increasing trends over KRB. The spatially averaged precipitation has shown an increasing trend at a rate of 28 mm/decade (Fig. 8.4(a)). Thus, although there is high spatial variability of precipitation over KRB, the annual average precipitation has shown an increasing trend over the basin. The spatial pattern of average air temperature over the basin is presented in Fig. 8.4(b). Higher average temperatures were observed toward the upper most portion of the basin covering few districts of Maharashtra and Telangana. Figure 8.4(b) shows the temporal trends of basin-averaged temperatures for the period of 1965 to 2014. Correspondingly, temperature has shown an increasing trend of 0.1 °C/decade (Fig. 8.4(b)).

For the assessment of precipitation and temperature over KRB for the future scenarios, the CORDEX simulations were used. The precipitation and temperature

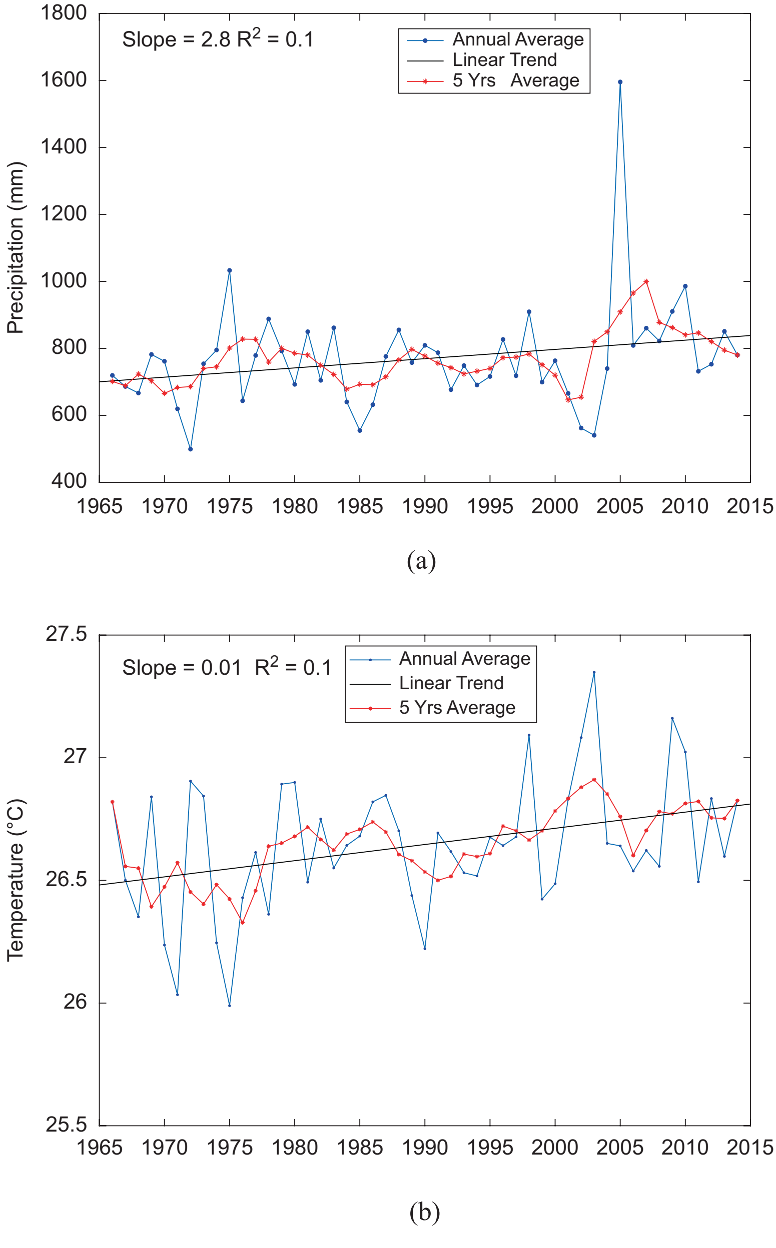

Fig. 8.4 (**a**) Precipitation and (**b**) temperature temporal trends in basin-averaged conditions from 1965–2003 to 2004–2014

data extracted from RCM outputs from 1965 to 2060, after bias correction, were used to estimate the precipitation and temperatures over KRB. Basin-averaged precipitation and temperatures were studied for two time periods of 2021–2040 and 2041–2060 along with historical time period of 1965–2003 and 2004–2014 as given in Table 8.1. The study of the compatibility of RCM projections with observed data sets is a prominent step (Singh et al. 2017). Therefore, the study compared the RCM climate projections with the observed data sets for historical period of 1965 to 2014 in reproducing the current climate variability. The bias-corrected monthly precipitation and temperatures from each CORDEX RCM model were well compared with the observed IMD data for the period of 1965–2014 (Fig. 8.5). The RMSE (R-square) values estimated between observed precipitation and each RCM model outputs of COSMO, REMO, and SMHI were estimated at 78.5 (0.2), 70 (0.23), 80

Table 8.1 Spatial average annual precipitation and temperatures for current (1966–2003, 2004–2014) and future period (2021–2040, 2041–2060) for KRB

Hydrological variable	RCM name	Current		Future	
		1966–2003	2004–2014	2021–2040	2041–2060
Average annual precipitation (mm)	Observed	733.12	894.47	–	–
	COSMO	757.91	698.27	762.82	807.52
	REMO	755.36	841.84	864.29	850.7
	SMHI	773.33	834.73	834.73	869.82
Annual temperature (°C)	Observed	26.6	26.7	–	–
	COSMO	26.53	27.05	27.71	28
	REMO	26.54	26.71	27.81	28.09
	SMHI	26.56	27.1	27.74	28.22

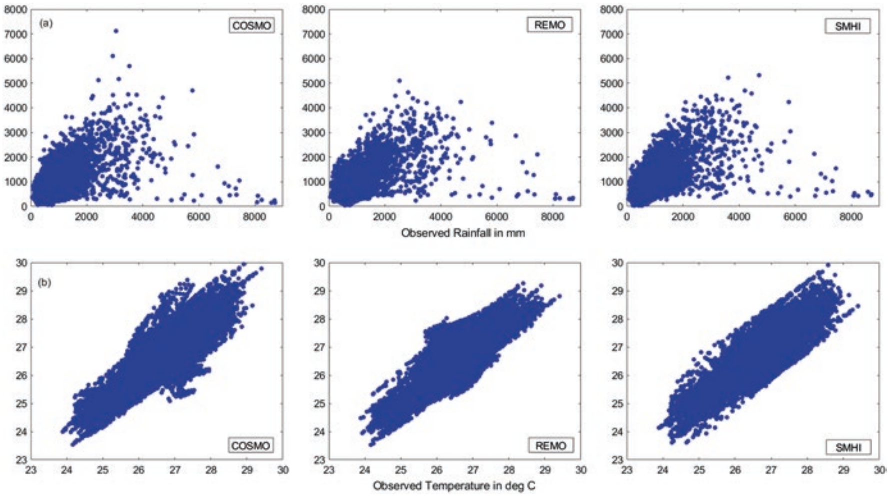

Fig. 8.5 Scatter plots of bias-corrected RCM model outputs of (**a**) precipitation and (**b**) temperatures for the period of 1966 to 2014

(0.15), respectively, for the period of 1966 to 2014, whereas the RMSE (R-square) values estimated between observed temperature and each RCM model outputs of COSMO, REMO, and SMHI were estimated at 1.9 (0.6), 1.6 (0.7), and 1.95 (0.52), respectively, for the period of 1966 to 2014. Among the selected three RCMs, the REMO model has shown best performance for simulating precipitation and temperatures over KRB. The precipitation has been predicted to increase under climate change signals with all three RCM models for the future periods of 2021 to 2060 over KRB. The increase in projections of annual average precipitation for the periods of 2021–2040 and 2041–2060 was compared with the observed data periods of 1966–2003 and 2004–2014 over KRB (Table 8.1) (Fig. 8.6(a)). The SMHI model has predicted highest increase of precipitation as varying from 101.6 and 136.7 mm for the future time periods of 2021–2040 and 2041–2060, respectively, compared to the current climate period of 1966–2003 over KRB. While the lowest precipitation projections, varying about 29.7 mm and 74.4 mm of increase for the period of

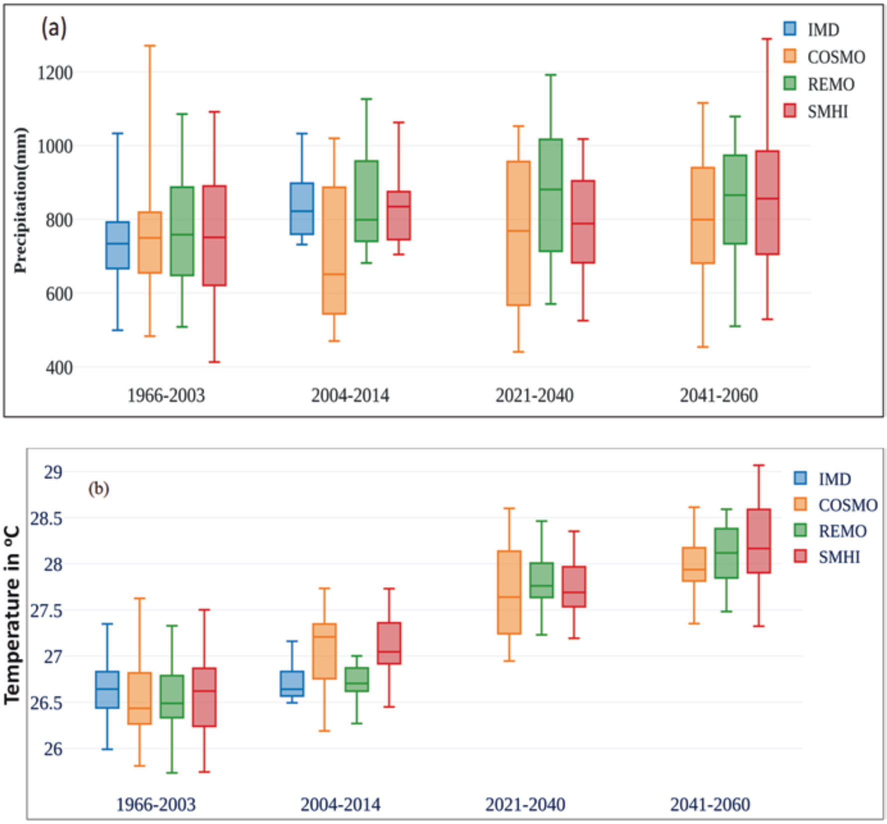

Fig. 8.6 Basin-averaged annual observed and predicted (**a**) precipitation and (**b**) temperatures for the period of 1966–2003, 2004–2014, 2021–2040, and 2041–2060 over KRB with various RCM model outputs

2021–2040 and 2041–2060, respectively, compared to observed period of 1966–2003, were noted with COSMO model outputs, moderate precipitation increasing projections were predicted with REMO for the RCP 4.5 for the future time periods of 2021 to 2060. Overall, the projected increase of precipitation under climate signals was predicted to be from 74.4 to 136.7 mm over KRB for the future time period of 2041–2060 compared to the observed periods of 1966–2003. About 1.06 °C–1.35 °C of increase in temperatures was predicted for the periods of 2021–2040 and 2041–2060, respectively, compared to the observed period of 1966–2014 over KRB (Fig. 8.6 (b)) (Table 8.1).

8.4 Conclusions

With consideration of fine resolution and simple in extraction, the RCM outputs can be used in the hydrological impact assessment studies under climate variability. Comparable to complex statistical downscaling models, which requires advanced computational expertise, the RCM projections can be used for brief analysis of spatiotemporal variability of climate variables at river basin scales. Such basic analysis of river basins can provide insights toward the variations of water-energy variables and consequent impact on basin yields and losses in terms of evapotranspiration, etc. The fine-resolution projections of precipitation and temperatures will provide a basis to study the streamflow variabilities with integration with distributed hydrological models. However, given the limitations toward the reliability of RCM outputs with observed climate variables and the use of bias correction method adopted, the CORDEX model projections have to be applied for impact assessment studies with proper evaluation. The bias-corrected projections should be evaluated for extreme precipitation and temperature indices at catchment scales to study the reliability of RCMs for modeling the extreme climate variables (Singh et al. 2017). Further, with the uncertainty involved in the projections of each RCM model and with each RCPs, uncertainty evaluation must be performed for climate variables and associated hydrological model. Given the variations over the climate variable projections from various climate models, RCPs and various water management models accumulate climate and model uncertainty in the impact assessment (Kay et al. 2009; Wu et al. 2015). Implementation of multimodal weighted mean variables to study the possible range of uncertainty bounds accumulating from various stages of decision-making and cascading of uncertainties (Rehana and Mujumdar 2014) can be potential future research problem. Further, the application of RCM model outputs for the hydrological impact assessment has to be validated by comparing the historical spatiotemporal variability of simulations of hydrological events. Thus, the simulations of hydrological, drought, irrigation, and water quality associated with RCM outputs must be validated with historical occurrence of events in terms of frequency, durations, and intensities along with spatial extents of the events. The use of RCM outputs for the assessment of hydrological studies at catchment scales will emphasize on the adaptive measures to be applied for the sustainable water resource management.

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Microorganisms in Maintaining Food and Energy Security in a World of Shifting Climatic Conditions

9

Nikita Bisht and Puneet Singh Chauhan

Abstract

Over the past few decades, science and technology has made great advancement to get familiar with the impact of climate change in different aspects of life worldwide. But still, climate change is one of the major concerns posing a threat to food and energy security. The present chapter discusses the influence of changing climatic conditions on food and energy security and how microbes can be used in the amelioration of stress induced by changing climate. In recent years, studies have shown that increased concentration of greenhouse gases is the main cause of climate change; therefore, it becomes necessary to decrease their concentration in the atmosphere, though shift in energy structure from finite sources to natural renewable sources might help. Therefore, use of fossil fuels must be significantly reduced to balance structural shifts improving energy self-sufficiency and enhancing energy security. The change in climate impedes crop, livestock and fisheries production and also increases the prevalence of pests in agricultural fields. The use of chemical fertilizers in agriculture not only influences environment negatively but hampers food security and energy structure of the ecosystem. However, the use of beneficial microorganisms for amelioration of stresses holds importance nowadays, especially with respect to changing climate and usage of chemicals in agricultural soils. The beneficial microorganisms can be the most promising approach for safe management practices in agriculture. Therefore, in the present scenario of shifting climatic conditions, food and energy security can be maintained by utilizing soil microbial diversity that will ultimately increase the economy by limiting food and energy security risks.

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Keywords
Food security · Energy security · Climate change · Microbes · Sustainability

9.1 Introduction

Climate change has arisen as a new problem worldwide. Increase in average mean annual temperature and precipitation globally are chief outcomes of climate change which are likely to enhance in the future (Misra 2014). Food and energy security are highly vulnerable to such outcomes and pose a serious threat throughout the world. Any alteration in climate adversely affects annual rainfall that is likely to hamper agriculture yield at an unprecedented rate (Thornton et al. 2014). Due to climate change, not only the mean temperature and annual rainfall pattern is disturbed but also extreme conditions like floods, drought and cyclones also become more frequent. The increasing population and urbanization have already created pressure on the existing sources demanding maximum yield on less land with less water and fertilizers than used previously. A further rise proposes an imbalance between the supply and demand that will further obstruct food and energy sustainability.

The major challenge in mitigating harmful effects of climate change is to manage global warming. Excessive emission of greenhouse gases (GHGs) in the atmosphere is the foremost reason for global warming. Earlier, to control and reduce emissions of major greenhouse gases, viz., carbon dioxide, methane, nitrous oxide, fluorocarbons and sulphur hexafluoride, and to build a framework for their elimination, major industrialized nations of the world did an international agreement at Kyoto, Japan (1997), known as Kyoto Protocol, but still shift in climate is a predominant problem. The climate change becomes an even more sensitive issue for developing countries where people depend more on land and agriculture for their livelihood. However, to achieve sustainable development under shifting climatic conditions, it is necessary to address food and energy security challenges harmoniously.

The development of shifting climate condition resilient agriculture is a challenging task, but incorporation of soil microbial diversity in this area can make this task easier. Since ancient times, it has been reported that soil microbiome maintains ecosystem functions, and exploitation of such microorganisms in an appropriate way might be the best solution for the problem of climate change in the context of food and energy security. The soil-inhabiting microbes assist plants in adaptation and developing tolerance and help in the mitigation of stresses related to climate change. Therefore, to successfully implement microbial technology for shifting climate scenario to ensure food and energy security, understanding microbial ecology for climate change adaptation and mitigation becomes a must.

9.2 Food and Energy Security Are Two Sides of the Same Coin Influenced by Climate Change

Before industrial revolution, sun was considered as the prime source of energy for photosynthesis that enabled plants to grow and serve as food for other living beings. But as time passed by, agriculture became more dependent on chemicals, so at present agriculture requires a large input of chemicals which in turn are synthesized using energy derived from fossil fuels. Besides, energy is also required for various other purposes like irrigation, farm equipment, product processing and transportation. Therefore, when shifts in climate negatively influence food security, it will simultaneously affect energy structure and energy security.

Figure 9.1 shows how change in climate affects available resources, which in turn influence food and energy security. It also illustrates the factors which can be the action fields for maintaining balance in food and energy and the possible outcomes of it.

9.2.1 Agriculture and Food Sustainability Under Shifting Climatic Conditions

The global population is increasing day by day and is anticipated to increase further by 2050 (Ringler et al. 2016). The increased population is a saddle for prevailing resources, which is further exasperated by urbanization and unbalanced use of fertilizers and pesticides. Despite technological advancements, including mechanization of labour and development of high-yielding varieties of crops, food security for all is still a major problem. Approximately, 2.0 billion people are undernourished globally, and amongst these children constitute major portions. These children are often short and thin for their age due to insufficient intake of food (Myers et al. 2017). Moreover, malnutrition is associated with approximately 3.0 million child deaths per year globally (Black et al. 2013). In the existing situation, where

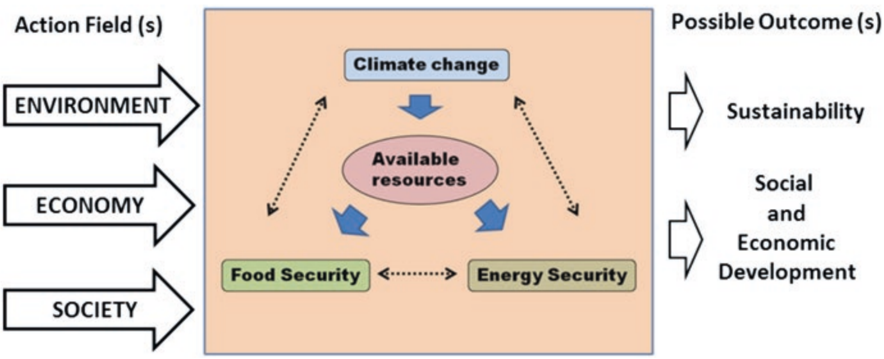

Fig. 9.1 Influence of climate change on food and energy security and its action fields and possible outcomes

population is increasing at a rapid pace, there is an urgent need to monitor global food demands. Added to challenge of providing ample food for all, other major constraints such as enhanced anthropogenic activities disturb the environment where actual global food production functions and imposes a lot of stress on land, water, etc. Therefore, the biggest challenge is to keep up with the ever-rising human needs with respect to transformation of earth's natural systems including weather ambience.

Agriculture is main source of economy for developing countries like India, and any shift in climatic conditions could have devastating implications on crop productivity. It is well characterized that climate change modulates a relationship between crops, pathogen weeds and pests by exasperating the balance between biophysical resources like sunlight, quality of soil, availability of water, temperature CO_2 concentration, etc. Nevertheless, manual labour, air pollution and pollinator abundance too have a major role in agriculture and can be easily influenced by climate change but are very poorly characterized.

Crop plants are often highly sensitive to variations in temperature and water. The land temperature worldwide has increased by 1 °C due to increased atmospheric GHGs when compared to the twentieth-century average (https://www.ncdc.noaa.gov/cag/time-series/). Under representative concentration pathway (RCP) 4.5, which is the moderate emission of GHGs in the atmosphere, there would be a continuous increase in CO_2 concentrations from the present level of 400 ppm to a level of 540 ppm by 2100 (Prather et al. 2013). However, according to IPCC (2014), if emission of GHGs becomes higher, termed as RCP 8.5, the level of CO_2 would reach 940 ppm by 2100, resulting in warming of land from 4.0 °C to 6.8 °C (https://www.ncdc.noaa.gov/cag/time-series/). Increasing temperature also affects water resources in a multitude of ways like shifting precipitation, early seasonal snow melt, loss of glaciers, etc. which affect agriculture yield drastically. The management and mitigation of agriculture risks linked to extreme events associated with climate change can help in achieving food security. Moreover, the use of crop breeding techniques might also improve the crop performance under shifting climate conditions. Use of crop breeding techniques might help in improving the performance under shifting climate conditions. Several studies have indicated that abiotic stresses in plants can be overcome by using crop breeding as a means of increasing productivity alongside climate change mitigation (Evenson and Gollin 2003; Burney et al. 2010). However, it is a very time-consuming and intense labour-demanding technique; thus, its implementation requires time. Therefore, management of food security and its development sustainably becomes a tedious task. Expansion, advancement and implementation of food security plan should be done appropriately and must comprise practices for dealing threats, tampering of products and their storage and distribution in a well-monitored way.

9.2.2 Energy Security and Shifting Climate Conundrum

Over the last few years, concern over security implications of climate shift has increased tremendously both locally and globally. Climate shift and energy security are often considered as friends with asymmetric benefits and are the key drivers for future energy policy (Chaturvedi 2016). Energy security is defined as continuous accessibility of energy sources to all the people globally that too at an affordable price as described by International Energy Agency. Energy security can be categorized as follows: (1) energy security which focuses mainly on investments to supply energy on time, simultaneously with sustainable environmental needs and economic developments, and, hence, considered under long-term goals; (2) on the other hand, security of energy which deals with energy system that respond instantly to abrupt change in balance between supply and demand is considered for short-term goals. The absence of energy security is mainly because of the absence of physical availability of energy along with non-competitive or excessively unstable rates that influence socio-economic issues negatively. Increasing population and needs are not the only problem for food security but also for energy security, and maintaining energy security in a world facing the problem of climate shift is a challenge.

However, technological advancements are likely to facilitate the way of living of people but still need consideration because these are the main sources of hazardous GHGs. At present time, reduced energy efficiency owing to large consumption of energy with high emissions has a whimsical effect on economic structure (Dodo 2014). Therefore, it is necessary to clearly understand the connection that climate shift and energy security share to cope with future stresses. Although the influence of shifting environmental conditions on energy security has attracted the interest of researchers and policy-makers in recent years, very less work has been done to understand the linkage between climate shift and energy security. To ensure sustainability of energy with rapid economic growth requires development of cost-effective policies to provide cheap and sufficient amount of energy along with the reduction in emission of harmful gases. Several studies conducted at local, national and international levels have analysed the drawbacks related with climate change and have highlighted the challenges associated with it (Dodo 2014; Di Gregorio et al. 2019). Nonetheless, the role of energy in modulating climatic conditions can be easily explained by points discussed further. Firstly, energy is responsible for around 60% of emissions at the global scale (Baumert et al. 2005). The control of emissions from energy will play a vital role in mitigation of issues related to shift in climate and support economic development and prosperity. Moreover, import of fossil fuels from unstable regions, or over-dependence on one supplier, is of great concern for many countries. To avoid such circumstances, use of renewable sources should be promoted that will also aid in climate change mitigation along with balancing energy security (Friedman 2005). Secondly, significance of climate change on environmental sustainability plays a vital role in human security as well (Dalby 2002). Therefore, efforts are needed to be made both conceptually and in practice to make energy security and climate-protection objectives fit together. The use of science and technology to increase efficiency of energy requiring equipments and power plants and their economical utilization can reduce a lot of energy use. The selection of fuel for generating energy defines the level of emissions; for example, when crude oil is used, the C emission factor is approximately 20 tC/TJ , whereas it is more when coal is used. Therefore, less carbon-intensive fuel should be used to reduce emissions thoroughly (IPCC 2007).

9.3 Microbes in Balancing Food and Energy Security

Microorganisms are smallest forms of life on the earth having largest uncultivated pool of biodiversity (Bhattacharyya and Jha 2012). These organisms play a critical role in every spectrum of life and microbial ecology and thus become the frontier in the present world facing several problems. Microbes are considered as the driving force for many functions of the ecosystem and thus play crucial role in maintaining agriculture and energy security (Bhattacharyya et al. 2016). The function of microorganisms in the context of plant growth and promotion under various stresses is well established and their role as biological control agent cannot be denied. The traits possessed by PGPR such as P solubilization, nitrogen fixation, production of siderophores, ACC deaminase, exopolysaccharides, phytohormones, etc. facilitate plants to grow efficiently under all circumstances. The rhizobacteria belonging to the genus *Pseudomonas, Bacillus, Rhizobium, Azotobacter, Paenibacillus,* etc. are involved in growth promotion in different crop plants such as tomato, rice, chickpea, millet, etc. Some of these are efficient biocontrol agents for fungal pathogens in crops. The role of fungi belonging to genus *Trichoderma* in biocontrol and nutrient acquisition is well documented. Therefore, beneficial phytomicrobiome (bacteria and fungi) present in soil and in different plant parts such as roots, leaves, stems, flower and fruit exert positive effects in the growth of plant and are essential for plant's life (Berg et al. 2016). Nonetheless, diverse conditions faced by plants lead to accumulation of diverse microbial population. However, not all the members of phytomicrobiome can be cultured in laboratories; they can be studied only with the help of metagenomics (Hirsch and Mauchline 2012). However, the role of unculturable microbes cannot be denied in plant development (Wintermans et al. 2016). The plant selects its rhizomicrobiome by exudation of various chemical compounds which are utilized by specific microbes (Trabelsi and Mhamdi 2013; Zhang et al. 2017). Some plant-exuded compounds act as signal molecules to attract selected microbes and regulate their activities (Nelson and Sadowsky 2015; Smith et al. 2017). The microorganisms produce quorum-sensing compounds for communication, and plants are reported to respond to these compounds (Chauhan et al. 2015; Ortiz-Castro et al. 2009). Ultimately, the phytomicrobiome present either in soil or in plant can probably be the best strategy to overcome stresses related to shift in climatic conditions and can also be used for its mitigation.

9.3.1 Plant Microbe Interactions Under Shifting Climatic Conditions

Shifts in climatic conditions affect soil microbial diversity that functions to maintain dynamics of ecosystem. A change in climate induces changes not only in plants but also in microorganisms and affects plant–microbe relations. The composition of soil microbiome is sensitive to changing pattern of climate such as carbon dioxide and rainfall which stimulate the growth of some microorganisms, while other microbial population are suppressed by these conditions (Ng et al. 2015). The changing pattern of rainfall enhances the incidence of water and drought stress that are unsafe for microbial life present in soil. This hinders beneficial microbes while promoting the development of pathogenic microorganisms (Magan et al. 2011). The literature available suggests that during wetting periods crops are prone to pathogenic fungi belonging to genus *Fusarium* and *Aspergillus,* which by producing mycotoxins contaminate the edible portion posing a threat to living beings (Wagacha and Muthomi 2008). During plant–microbe interactions, plant root exudates act as signals to attract microorganisms which sense chemical messages and activate complex cascade to initiate several responses in plant (Glick 2012). The communities of plant beneficial microbes change significantly under varying seasonal precipitation that alters the dynamics of functional microbes (Cregger et al. 2012). The soil microbiome contributes to natural emission of gases like CO_2, CH_4 and N_2O, but their role in the utilization of greenhouse gases is also well elaborated and therefore can be utilized in mitigating the effect of climate change (Bardgett et al. 2008; Mohanty and Swain 2018). The microbial inoculants have the ability to adapt various agroclimatic conditions having diverse temperature, moisture, pH and salt concentration. Additionally, soil microbes are likely involved in biogeochemical cycling of elements like C, N, etc., and thereby increase productivity and influence GHG budget by limiting emission per unit productivity of GHGs by reducing the input of chemicals in different forms. Recently, Backer et al. (2018) have reviewed that changing climatic conditions will worsen agricultural conditions by making abiotic stresses more frequent and in this scenario plant beneficial microbes could play a key role in improving productivity. Therefore, accrued benefits from above-mentioned traits of microorganisms can be regarded as their prominent role in mitigation of climate change. Figure 9.2 shows how climate change affects food and energy security and how microbes can be beneficial in this context.

9.3.2 Microbes as a Source of Renewable Fuel

Climate change has not only enhanced emergence of pests and pathogens in agriculture but has also affected soil quality negatively. To improve soil quality, a large pile of fossil fuel is used for generating energy, to derive synthesis of chemicals needed in agriculture in various forms such as fertilizers and pesticides. Moreover, advancement in technology has led to mechanization of agriculture which consumes a large part of energy. Use of plant probiotics can, however, reduce the use of chemical

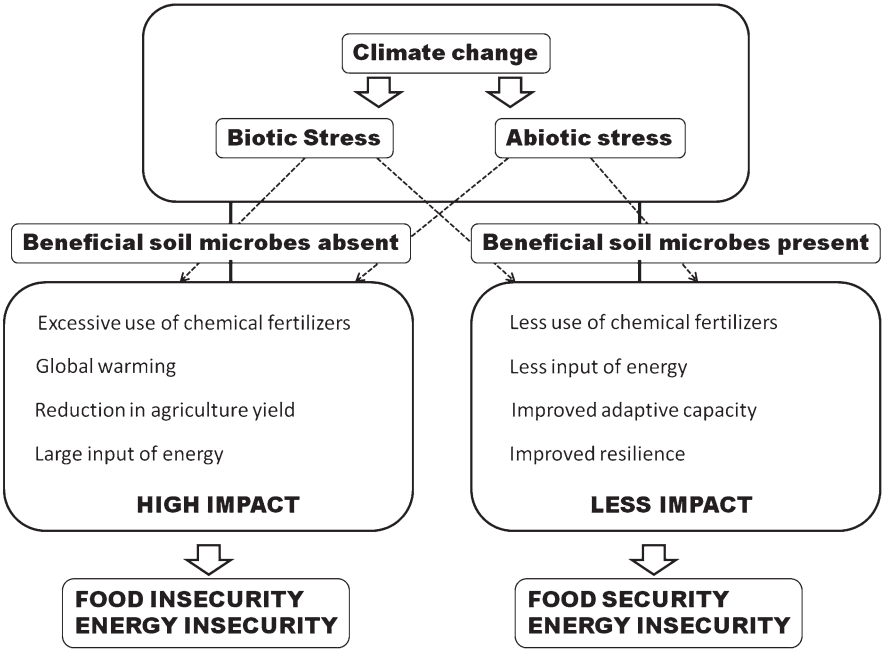

Fig. 9.2 Influence of beneficial microbes in mitigation of climate change-induced stress

fertilizers and pesticides and thereby reduce energy input required for the synthesis of chemicals (Russo et al. 2012). Various bio-control agents are known which can be used efficiently for controlling pests and pathogens in field such as *N. fresenii*, *B. thuringiensis* and *Trichoderma*. *N. fresenii* is reported to control cotton pest *A. gossypii*, and rust fungus *M. cryptostegiae,* whereas *B. thuringiensis* kills lepidoptera and diptera larvae. *Trichoderma* is a well-established bio-control agent against several pathogens in a variety of crops (Martínez et al. 2015; Marra et al. 2019).

To replenish exhausting fossil fuel reserve is an impossible task because it takes hundreds of millions of years to produce fossil fuels; however, development in science has made microbial biofuels closer to economic reality and an alternative for fossil fuels. One benefit of using microbes for producing biofuels is that they can be cultivated and replenished easily. Overall, due to multifaceted ability as well as effortlessness associated with microbes, they might be a promising approach to substitute a quantity of our fossil fuel usage. Certainly, employing sun's energy in solar power, photovoltaics, etc. helps to congregate human demand, but use of energy stored in waste biomass (Vaish et al. 2016, 2019) and water can undeniably contribute in energy security. But the major drawback associated with microbial factories is that they sometimes evolve in an unexpected way, so it becomes challenging to figure out how to get maximum output from them.

9.3.3 Need to Exploit Microbes for Climate Change Mitigation

Microbial activities are crucial for sustainability of life on earth. Whether it is degradation of organic matter, bioremediation, or plant growth promotion, microbes are essential. Consequently, conservation of microbial diversity becomes necessary (Colwell 1997). At present time, when population is increasing rapidly and climate change problems have surged, plant–microbe interaction and microbial communities are also affected severely. The higher concentration of CO_2 in atmosphere limits nutrient acquisition rate, thereby increasing fertilizer input and consequently energy (Bhattacharyya et al. 2016). Microbial metabolic activity alters carbon and nitrogen exchanges between land and atmosphere in many ways, on the basis of which microbes are classified into different categories. One group is of methane oxidizing microbes, known as methanotrophs, which act as a sink for methane emission, reducing its escape to the atmosphere. Apart from these, exploitation and management of plants probiotics and nitrifying bacteria that can be used as biofertilizer and bio-control agent can contribute to both climate change adaptation and mitigation (Bhattacharyya et al. 2016). Recent advancement in genomics has made microbial genome sequence easily available and, thus, genomic approaches can be powerful tools for food and energy sustainability. Further, novel genes related with tolerance for several harsh conditions can be identified using the above-mentioned technique. Research should be focussed more on to exploit diverse microbial communities and efficient strains that can help in combating climate shift in future.

9.4 Conclusion

Rapidly increasing population, disproportionate usage of chemicals, and decreasing cultivable land and water resources have affected food and energy security profoundly. Recently, research has indicated that shifting climatic condition has made conditions even worse because extremes of climate have enhanced problems like drought, cyclone, floods, etc. The rising concern about food and energy security has attracted the minds of scientists to propel investigation for alternative eco-friendly approaches. In this regard exploitation of diverse microbial population present on earth can be the apt approach for maintaining ecosystem function and for amelioration of stress induced by climate change. Beneficial microbes have already been documented as an appropriate choice for plant growth and development under various biotic and biotic stresses and, therefore, offer an innovative crop protection tool for climate change too. Smart sustainable development needs a better understanding of interactions between plants, microbes and global climate change that will help to fight against climate change.

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Engineering Photosynthetic Microbes for Sustainable Bioenergy Production

10

Amit Srivastava, Marta Barceló Villalobos, and Rakesh Kumar Singh

Abstract

The implementation of photosynthetic organisms has received tremendous attention in the last two decades in order to achieve the products of high industrial value at the minimal cost of environmental carbon dioxide, water and nutrients. The advancement of molecular biology tools including the availability of completely sequenced genome of a variety of photoautotrophs has made their genetic modification possible for it. In the past decade, there was an increase in the discovery of novel biosynthetic pathways in photosynthetic organisms, but there are several challenges that need to be reported and solved for developing an improved engineered strain with desired traits. Genetic engineering tools are required not only to introduce novel pathways in the photosynthetic organisms but also to modify host metabolism. For solar biofuels, most of the metabolic engineering attempts have been applied on cyanobacteria and microalgae, mainly focused in this chapter. To modify cyanobacteria for production of biofuel, the efficiency of photon conversation should be targeted which in turn may allow effective utilization of solar energy. A combinatorial approach for developments of these strains, their selection, genetic engineering, optimization of bioreactors and processing technology may pave the way for the production of biofuels that can ensure future energy security in a sustainable manner. In a larger perspective, efficient

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photosynthetic machinery provides a solution for an efficient and large-scale biofuel production which holds the promise of replacing harmful non-renewable fossil fuels, which may eventually delay a shift in global climate change.

Keywords
Biofuel · Cyanobacteria · Genetic engineering · Microalgae

10.1 Background

Humans have adversely changed the living conditions on earth with their ever-growing demand for energy. To meet such a large sum of energy, a great amount of fossil fuel has been combusting every day that eventually increased the global carbon dioxide level and as a result earth's climate started to react more severely. In the year 2011 alone, 82% of global primary energy usage was based on fossil fuels (EIA 2012). It is clear that the overuse of petroleum, coal and natural gas resulted in major global environmental issues (Goncalves et al. 2016). This climate change is negatively influencing the life on our planet (Kerr 2007), which, if not checked sooner, may cause a permanent threat to the ecosystem and environment on our planet. These issues pose two important concerns for mankind: (1) to find a sustainable and clean energy source soon and (2) to find an alternative source of energy that can be used if the non-renewable source will be exhausted or deplete to a critical level. These are the most challenging problems humankind is going to possibly face in the future since they are directly associated with our economic development, global stability and strategic planning (Mata et al. 2010).

To valiantly deal with these circumstances, a growing popular option among scientists, industrialists and ecologists is "biofuel", which is produced by means of biological processes. Biofuels are carbon-neutral (minimal CO_2 output) fuels which can be reproduced relatively in a short period of time and do not contribute to the rise in global atmospheric CO_2 levels upon combustion (Zeman and Keith 2008). Gasoline and diesel can be replaced by relatively less harmful biofuels such as bioethanol and biodiesel, respectively (Mata et al. 2010). Biofuel in form of biodiesel is synthesized from transesterification of fats/oils, and the total content of solid particles and polycyclic aromatic hydrocarbons are significantly lower in respect to typical diesel fuel that is derived from fossils (Zajac 2008). Today the primary sources of biodiesel are vegetable oils. On earth's surface, approximately 200 W/m^2 solar energy is available per year, out of which a large proportion (29.2%) is harvested by photosynthesis (Lan and Liao 2011). This is a significant amount of renewable and sustainable energy source, which could be used for the synthesis of biofuels. With recent advancement in photosynthesis research, photosynthetic microbes such as microalgae and cyanobacteria have emerged as one of the most promising host organisms for biofuel production (Savakis and Hellingwerf 2015).

Microalgae has the impeccable ability to grow whenever they receive a sufficient amount of light and water source; however, for the production of biofuels at a commercial scale, a larger sum of biomass is needed which is not possible through natural means. Therefore, an artificial cultivation system should be required for growth in order to improve the overall process. The conditions that should be considered for this might be CO_2, H_2O, light, salts and temperature (Chisti 2013). According to the reports, approximately 183 tons of CO_2 consumed by algae leads to the production of 100 tons of biomass (Chisti 2013). Despite the fundamental constituents such as carbon and hydrogen, the inorganic macronutrients such as nitrogen, phosphorous and iron are the important components of algal biomass (Grobbelaar 2003), which is represented by the formulae $CO_{0.48}\ H_{1.83}\ N_{0.11}\ P_{0.01}$. For commercial growth of microalgae at the optimum conditions, the main cultivation systems extensively used are closed photobioreactors and open ponds.

10.2 Photosynthetic Factories for Biofuel

Cyanobacteria are prokaryotic microorganisms that capture their energy from photosynthesis via utilizing CO_2 and light and in return produce oxygen as a by-product and certain useful products (Fig. 10.1) (Machado and Atsumi 2012). Microalgae are

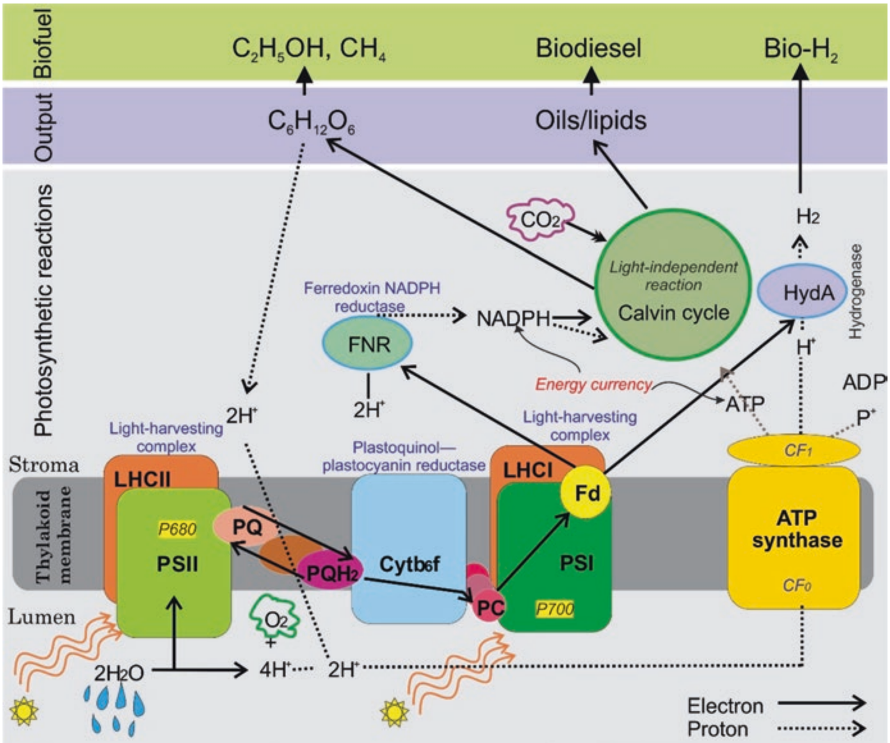

Fig. 10.1 Sketch of fundamental process of photosynthesis utilizing CO_2 and light for production of O_2 as a by-product and other useful products

slightly complex as they are eukaryotes and similar to cyanobacteria having the capability of performing photosynthesis (Sydney et al. 2010). Both play a crucial role for primary production in aquatic ecosystems and participate in the utilization of global CO_2 (Patel et al. 2019). On the other hand, heterotrophic bacteria utilize organic carbon sources (originally derived from photosynthesis), which increases the overall number of steps involved in metabolic reactions to generate the resultant fuel compound. In the timeline of recent metabolic engineering research, two heterotrophic model organisms *Escherichia coli* and *Saccharomyces cerevisiae* (Budding yeast) have been the main sources of microbial fuels. However, there are some drawbacks associated with them such as the cost of their organic feedstock, fuel extraction recovery cost and the cost for additional chemical modifications (Rude and Schirmer 2009). In comparison to heterotrophic microbes, plants represent a much attractive model for biofuel production as they can synthesize fuels directly from CO_2 and do not need expensive feedstocks. However, the use of a food source for fuel, need for scalability, the requirement of freshwater resources and the need of land for their growth are some convincing negative aspects of plants as biofuel production hosts (Al-Haj 2016). Among these options, photosynthetic microbes (microalgae and cyanobacteria) seem to be the best alternatives (Ducat et al. 2011; Dismukes et al. 2008). As a proof, if we compare sugarcane (for ethanol), palm oil (for biodiesel), algae (for biodiesel) and cyanobacteria (for ethanol), the current yield (ha^{-1} $year^{-1}$) is 6000 litre, 5500 litre, 58,700 litre (Maximal theoretical yield) and 50,000 litre, respectively (Anemaet et al. 2010).

Figure 10.2 represents a flow chart that shows the basic steps involved in the production of cyanobacterial and microalgal biofuels. Microalgae do not require a large land area and irrigation for growth. Since microalgae are resilient to environmental stress and cosmopolitan, several species of microalgae can live and are able to thrive in diverse and adverse environmental conditions, which gives them an advantage over other systems for the production of biofuel that needs tedious optimization efforts (Jagadevan et al. 2018). Furthermore, in past few years, several compatible genetic manipulation tools have been developed for many photosynthetic microbes. In addition, their growth conditions are continuously being optimized for similar and other algal species to broaden their applications (Nasir et al. 2019). In addition, phototrophic microbes are an efficient transducer of solar energy (3%) to biofuels as compared to higher plants (0.5%) (Melis 2009). Moreover, the photosynthetic ability of algae is approximately three times higher than terrestrial plants, by virtue of their simple cellular structure (Shimizu 1996).

One more benefit of phototrophic microbes is that they can grow within an enclosed photo-bioreactor (Angermayr et al. 2009) and are able to withstand higher CO_2 content in gas streams (Zhou and Li 2010). Designing photobioreactors is a very important factor to take into consideration. There are two types of photobioreactors: open and closed. They must be chosen depending on the final use of the biomass. In the case of high-quality biomass as a cosmetic or nutraceutical use, close photobioreactors are recommended. In the case of biofertilizers or aquaculture feed, open reactors should be used. That is because open reactors are more vulnerable to environmental contamination than the closed ones. In summary, the important

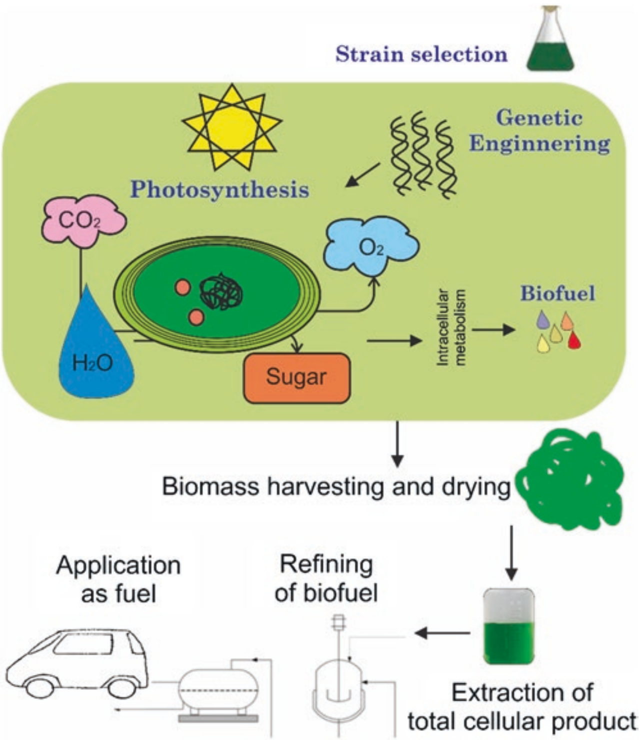

Fig. 10.2 Flow chart of basic steps involved in production of cyanobacterial and microalgal biofuels

features that make a phototrophic microbes as a good alternative for biofuel production is their fast growth rate, simplicity of cultivation and the availability of facile genetic manipulation techniques to alter the fundamental aspects of their cellular metabolism (Surzycki et al. 2009). Yet, the most advantageous feature enabling ongoing progress in the application of algal biotechnology is the availability of robust and well-established transformation systems for these cells (Purton et al. 2013). A beneficial feature of microalgae making it an easy host for biofuel research is that many of them are considered as GRAS ("generally recognized as safe") organisms, attributed to the purification of the bio-available products which can be substantially reduced or eliminated altogether (Matos 2017).

Among microalgae, *Chlorella sorokiniana* and *Chlamydomonas reinhardtii* have been studied as a potential candidate for biofuel production (Illman et al. 2000; Gouveia and Oliveira 2009), and genetic manipulation techniques are widely available for these species. Further, between cyanobacteria and microalgae, cyanobacteria have even faster growth rates and are easily amenable to genetic manipulation (Berla et al. 2013). Two model cyanobacterial strains, *Synechocystis* sp. PCC 6803 and *Synechococcus* sp. PCC 7002, represent the most studied system for biofuel production to date. Interestingly, *Synechocystis* (glucose-tolerant strains) can grow heterotrophically (in the absence of photosynthesis) (Vermaas 1998), which gives it an added advantage as a model strain to study the role of essential photosynthetic genes. The availability of complete genomic sequence has facilitated the biotechnological research on these organisms as their genomics, transcriptomics and proteomics information can be easily extracted (Ikeuchi and Tabata 2001) from web-resources (e.g. CyanoEXpress: http://cyanoexpress.sysbiolab.eu/). This huge amount of information has allowed the appropriate genetic engineering of these strains by pathway modification (Wu and Vermaas 1995), which allowed the detection and analysis of bottlenecks for improved metabolic production of bioenergy compounds such as hydrogen and ethanol (Knoop et al. 2010). A good example of metabolic engineering success in cyanobacteria is an improved strain of *Synechocystis* PCC 6803, known as the iSyn731 strain, that integrates all the functions and combines them to an improved metabolic capability (Berla et al. 2013). This strain contains nearly 322 unique reactions particularly in lipid biosynthetic pathways (Saha et al. 2012).

10.3 Biosynthetic Pathways for Biofuel Production: Promises and Challenges

In order to achieve the fundamental goals of biofuel production, researchers have been able to introduce novel pathways utilizing the existing molecular biology resources and knowledge. Although these efforts have rapidly increased the number of synthetic and engineered pathways in cyanobacteria, many bigger problems are still needed to be solved. For instance, less is known about how to modify the genetic makeup of the host cells/transportation system to improve the excretion of the intracellular compound from the cytoplasm during the growth of cyanobacteria (Niederholtmeyer et al. 2010). Another problem with cyanobacteria is that many biofuel-producing pathways in the cells are using anaerobic fermentative metabolism for production of reduced metabolites which involves oxygen-sensitive enzymes. Since cyanobacteria are dependent on oxygenic photosynthesis for their survival, spatial compartmentalization of the heterologous enzymes is a crucial aspect that should not be overlooked while considering metabolic engineering (Agapakis et al. 2012). Further, the toxicity caused by end product in higher titres can impair the cell growth as well. Thus, there is also a need to study the tolerance to biofuel compounds in phototrophic microbes (Anfelt et al. 2013). In light of that, it was reported that overexpression of a sigma factor (a transcription regulator protein) gene, *SigB* in *Synechocystis* PCC 6803, increased butanol tolerance, which demonstrated that genetic manipulation of transcriptional regulators can be a useful tool to improve metabolic pathways in the direction of biofuel production and consequent tolerance against biofuel-associated metabolites (Kaczmarzyk et al. 2014).

In order to produce fuel compounds in cyanobacteria, basically, the photon conversion efficiency needs to be improved, which would allow more effective utilization of sunlight flux (Badger and Price 2003; Ducat et al. 2012). Furthermore, pathways are needed to be optimized for host metabolism for increased flux. An example of this approach is the adjustment of heterologous biofuel pathways from *Clostridia*, by excluding oxygen-sensitive bioconversion and introducing oxygen-tolerant enzymes (Lan et al. 2013). Alternatively, the separation of oxygen-sensitive biological processes could also take place spatially, by targeting nitrogen-fixing heterocyst (Ihara et al. 2013; Savakis and Hellingwerf 2015).

In cyanobacteria, if energy storage metabolism associated with glycogen and polyhydroxybutyrate (PHB) are inactivated, the extra carbon can be directed towards the formation of products (Panda et al. 2006). Therefore, there is not only a need for the introduction of novel target pathways but also a radical modification of host metabolism (Savakis and Hellingwerf 2015; Wang et al. 2013). It has also been reported that in cyanobacteria when decarboxylation and phosphodiester bond cleavage reactions are modified, it can cause a diversion in the pathway for improved product synthesis (Savakis and Hellingwerf 2015; Oliver et al. 2013). Similarly, the overexpression of alcohol dehydrogenase and pyruvate decarboxylase leads to enhanced production of ethanol in *Synechococcus elongatus* PCC 7942 (Deng and Coleman 1999). In *Synechococcus* sp. PCC 7002, carbon flux was directed towards D-mannitol production using mannitol-1-phosphate dehydrogenase and mannitol-1-phosphatase (Jacobsen and Frigaard 2014).

Apart from scientific efforts for rewiring native metabolic pathways, there are also interesting examples available for construction of new pathways in the microorganism. One such example is the enhanced production of farnesene in *E. coli* by Wang et al. (2011) via the reconstruction of the yeast mevalonate pathway. Farnesene is categorized as sesquiterpenes which are important materials in the pharmaceutical industry. Further, in a recent successful attempt, the reactions and enzymes involved in chlorophyll biosynthesis have been reconstituted in *E. coli* expressing the full pathway accumulating chlorophyll (Chen et al. 2018). However, they are not capable of showing any photosynthetic activity as chlorophyll is just one of the main components needed for photosynthesis. Nonetheless, this report is optimistic news for cyanobacterial synthetic biology for future genetic manipulation of biofuel pathway engineering.

It is also useful to consider that while optimizing metabolic pathways, it is a necessity to maintain a balanced redox state in the engineered microbes (Mukhopadhyay et al. 2008), to avoid the accumulation of toxic by-products that will ultimately reduce the desired product formation. Furthermore, low activity of pathway enzymes can also limit the production potentials; therefore, it is an important factor that needs to be addressed while considering regulation in pathway engineering.

10.4 Tools for Manipulating the Photosynthetic Pathways

Genomic sequence information along with genetic engineering tools and methods are being developed and getting advanced rapidly for the modification of cyanobacterial and microalgal species in the last two decades. Molecular biology techniques employed to engineered cyanobacterial and microalgal species enlisted in Table 10.1.

Table 10.1 Molecular biology techniques employed to engineer cyanobacterial and microalgal species

Species	Technique	References
Anabaena PCC 7120 (nitrogen-fixing, heterocyst forming, filamentous cyanobacterium)	Antisense RNA	Srivastava et al. (2017)
Chlamydomonas reinhardtii (single-cell green alga)	Chloroplast genetic engineering, delete 'redundant' pathway, insertional mutagenesis, MicroRNAs, zinc-finger nucleases	Chung et al. (2017), Sanz-Luque et al. (2016), Li et al. (2010), Sizova et al. (2013), and Wannathong et al. (2016)
Chlorella pyrenoidosa STL-PI (freshwater green algae)	Delete 'redundant' pathway	Ramazanov and Ramazanov (2006)
Nannochloropsis sp. (non-motile microalgae)	CRISPR/Cas9, Homologous recombination	Kilian et al. (2011) and Wang et al. (2016)
Phaeodactylum tricornutum (marine and pinnate diatom)	Delete 'redundant' pathway, Meganucleases, TALENs	Daboussi et al. (2014), Weyman et al. (2015), and Yang et al. (2016)
Synechococcus elongatus PCC 7942 (freshwater unicellular cyanobacterium)	CRISPRi, homologous recombination	Huang et al. (2016) and Savakis and Hellingwerf (2015)
Synechocystis sp. PCC 6803 (unicellular, freshwater cyanobacterium)	Site-directed mutagenesis, sRNAs deep sequencing	Savakis and Hellingwerf (2015), and Xu et al. (2014)

Cyanobacteria can obtain exogenous DNA by natural transformation (Porter 1986) or can intake plasmid DNA by triparental conjugation using *E. coli* strains (Elhai and Wolk 1988); however, natural transformation is still the primary way of mobilizing the foreign DNA into unicellular cyanobacteria (Golden et al. 1987). Conjugation method involves the transfer of foreign DNA from a donor strain to a recipient strain via cell-to-cell contact (Stucken et al. 2012). For the strains that are not naturally transformable, one common strategy is electroporation, where the cells are exposed with an electrical field leading to DNA uptake by cells due to temporary loss of semi-permeability of cell membranes (Tsong 1989). Regarding microalgae, which are a bit complicated than cyanobacteria as they require two separate transformation location, either nuclear or chloroplast (Gong et al. 2011), the most suitable and efficient method for the delivery of foreign DNA is microparticle (either tungsten or gold coated with DNA) bombardment using the biolistic gun method (Heiser 1992). This method is particularly effective for the delivery of DNA into the chloroplast as the DNA must pass through multiple membranes. Once inside the organelle, the foreign DNA integrates into the genome of chloroplast via homologous recombination. Other than this, one popular, simple and efficient method for the nuclear transformation of *C. reinhardtii* is agitation of cell/DNA suspension with ~0.4 mm glass beads (Kindle 1998). In this series of methods, agitation with silicon carbide whiskers (Dunahay 1993), sonication (Jarvis and Brown 1991) or co-cultivation with *Agrobacterium tumefaciens* (Kumar and Rajam 2007) have also proved to be suitable for nuclear transformation of microalgae.

Except for transformation, other tools such as "Bio-Brick" method are quite important for successful genetic manipulation of desired genes in organisms. Bio-brick method involves the expression of desired genes in cells by the addition of recombinant plasmids that are constructed to contain genetic "parts" such as promoters, ribosome-binding sites, genes, terminators and other regulatory elements in microorganisms (Berla et al. 2013; Huang and Lindblad 2013). This modern tool is now a valuable technology to design a programmed cell with desired traits, where the assembly of the biological parts occurs in a hierarchal manner (Andrianantoandro et al. 2006).

Further, gene modification is also a key factor for successful development of engineered algal strains. The most common approach in algal synthetic biology is *cis* gene modification (through chromosomal editing) (Berla et al. 2013), although *trans* gene modification (through foreign plasmid addition) is also occasionally used. If we look at further improvement, modernization of DNA synthesis technologies has allowed the design of coding sequences and the use of codon optimized *trans* genes to improve the heterologous protein expression in cyanobacterial cells (Gustafsson et al. 2004).

The functional genomics toolbox of cyanobacteria consists of two basic strategies to abolish gene function: (a) gene knockout and (b) gene knockdown. Gene knockout strategy is a tool of reverse genetics, which is used to determine the functional role of the target gene by knocking out that gene either by gene deletion or by gene inactivation leaving all other genes unaffected. Gene knockout through insertional inactivation and in-frame deletion has been routinely employed to block the function of the target genes in cyanobacteria, but in some cases, the mutants are not viable and/or cannot segregate completely due to essential life function encoded or controlled by them. Therefore, to study such essential genes, instead of making the cells completely devoid of their gene product, their transcript levels are targeted by antisense RNA (asRNA) for their down-regulation (Blanco et al. 2011; Lin et al. 2013). In contrast, Antisense RNA approach is not only promising for the study of essential genes, but it can also provide an advantage to tune-up or tune-down the expression of genes when controlled under a regulatable promoter (e.g. copper-responsive PpetE or nickel inducible PprsB). Promoters are important constituent for controlled gene expression and crucial for asRNA-mediated approach in a cyanobacterium. Native promoters from the genes related to photosynthesis (PrbcL, Pcmp, Psbt, PpsaA, PpsaD, PpsbA1, PpsbA2 and Pcpc) have been investigated for their potential in gene expression in cyanobacteria. Many studies have shown that higher concentration of antisense RNA is important for efficient suppression of gene expression, which could easily be achieved by using strong promoters (Robert et al. 1990; Cannon et al. 1990; Van der Meer et al. 1992). Besides native promoters, heterologous promoters can also be utilized in cyanobacteria. Notably, some strong *E. coli* promoters (e.g. Ptac/Ptrc) have shown to express the target genes in higher levels in cyanobacteria, whereas others (e.g. Plac, Ptet, and λ PR) display little to undetectable activity in *Synechocystis* (Wang et al. 2012). To find out the role of a unique sigma factor, SigJ in *Anabaena* PCC 7120, Srivastava et al. (2017) employed antisense RNA-mediated knockdown technique, achieving an approximately three-fold down-regulation of sigJ mRNA in the knockdown mutant eventually increasing its carotenoid (myxoxanthophylls) content and improved photo-protection, supporting the feasibility of this technique in both basic and applied research.

Further, among all the tools used in metabolic engineering, the choice of plasmid vectors is elementary while considering transformation in cyanobacteria. They can be categorized into two groups based on their mode of replication inside the host (Koksharova and Wolk 2002): (1) integrative plasmids, which cannot replicate independently and would be lost eventually in further cell divisions (Wang et al. 2012), and (2) replicative plasmids, which are capable of maintaining themselves stably in the cells and are able to replicate in both cyanobacteria and *E. coli* (Deng and Coleman 1999, Koksharova and Wolk 2002; Wang et al. 2012). A number of replicative plasmids harbouring diverse selectable markers and RSF1010-derived plasmids have been generated for cyanobacteria (Berla et al. 2013; Golden et al. 1987; Wang et al. 2012). However, to express the biofuel-related genes, only a few expression plasmids are available for cyanobacteria. Generally, the native plasmids are stable inside the cells and hence a good candidate to modify for genetic engineering applications. Several native high copy number plasmids were already reported in cyanobacteria, which could be good candidates for the construction of cloning/expression vectors as they provide the possibility of isolation, restriction and ligation in a similar way to *E. coli* (Miyak et al. 1999).

10.5 CRISPR/Cas Gene Editing Tool as an Emerging Approach for Engineering Biofuel Production

Many bacteria and archaea have an adaptive immune system called CRISPR-Cas9 system (Clustered regularly interspaced short palindromic repeats/CRISPR associated proteins), which has been widely employed for gene inactivation and expression modification in several organisms (Peters et al. 2015; Hsu et al. 2014). The main advantage of this technique is multiplexing and marker less modification of genes. This allows a faster construction of strains with more than one modification in a relatively shorter time (Behler et al. 2018). In principle, the prokaryote intakes a piece of invading virus/plasmid DNA (the protospacer) and incorporates in a form of array in the genome. Thus, with each intake, a new piece is incorporated in the array and the host immunity further grows (Horvath and Barrangou 2010). Adjacent to the CRISPR array, often Cas9 protein is present that eventually carries out the immune response (Horvath and Barrangou 2010; Sander and Joung 2014). The main function of the Cas9 protein is to cut DNA and make a double-strand break. Scientists have been using it for gene editing using the CRISPR/Cas9 system by taking advantage of the host's own immunity and DNA repair strategy. Besides that this system is also used for modifying the gene expression (La Russa and Qi 2015). Further, this technique was also further improvised to down-regulate the genes by mutating the catalytic active site of Cas9 making Cas9 dead protein (dCas9) which stably binds and interferes with transcription of the target genes but does not cleave (Qi et al. 2013; Zhang et al. 2017). Gene editing in *Synechococcus elongatus* PCC 7942 and *Synechococcus elongatus* UTEX 2973 has been already carried out using *Streptococcus pyogenes*-derived CRISPR-Cas9 system; however, the high expression of Cas9 effector proved to be toxic for the cells (Li et al. 2016; Wendt et al. 2016). Further, this technique has been tried on *Synechocystis*, *Anabaena* PCC 7120, *Phaeodactylum tricornutum*, *Nannochloropsis* spp. and *Chlamydomonas reinhardtii* (Ungerer and Pakrasi 2016; Daboussi et al. 2014; Weyman et al. 2015; Wang et al. 2016; Huang et al. 2016; Baek et al. 2016), which gave promising results. Therefore, this genome editing tool is providing a new insight for microalgae-based biofuel applications.

10.6 Future Prospects

A photoautotrophic microorganism is well-equipped with sophisticated biosynthetic pathways and thriving on least of nutrient supplements with a relatively faster growth rate. They are gaining much attention for their ability to produce biotechnologically important products in an environmentally sustainable manner. Until now, it is not considered a very cheap technology which must be improved to have a competitive price. Thus, recycling of nutrients and water by using wastewater as an input should be taken into consideration to make this technology competitive into the market. However, higher productivity and genetic makeup for production of complex molecules make them a promising candidate for future biofuel production. Therefore, it is seemingly desired to design cyanobacterial and microalgal cell factories utilizing available synthetic biology resources and metabolic engineering approaches. However, it is imperative to gain an in-depth knowledge of metabolic regulation and mechanism of the biosynthetic pathway to improve the strain for desired traits. A collective effort of multi-omics approach is needed to improve the production and tolerance (in the host) of biofuel-related product.

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Ensuring Energy and Food Security Through Solar Energy Utilization

A. K. Singh, Surendra Poonia, P. Santra, and Dilip Jain

Abstract

Solar devices are suitable for areas having higher solar radiation with more than 300 days of sunny days. The solar energy has several applications in agriculture, rural development and cottage industries. Solar pumping can be useful in irrigation and solar PV (photovoltaic) sprayer and duster in plant protection in addition to power generation. Solar dryers can dry fruits and vegetables efficiently and effectively, and animal feed solar cooker can boil animal feed for milch animals which will result in increased milk production. Solar PV winnower can separate grains from straw. In addition, solar devices can melt wax for making candles. Solar still can make distilled water. These activities will increase farm income and reduce losses. Overall, the scope of different solar energy sources is enormous especially in villages for the benefit of farmers.

Keywords

Solar PV pump · PV sprayer and duster · Solar dryer · Winnower-cum-PV solar dryer · Animal feed solar cooker · Wax melter · Solar still and agri-voltaic

11.1 Introduction

The progress of any region is reflected in its quantum of energy consumption. With a view to keeping pace with development, we have to grow our energy resources by at least 6%. There is already shortage of electricity, reflected in power cuts notwithstanding enhancement of electricity production of several folds in the country. The problem is more severe in context with villages in the country where some 70% of population live and have agriculture as the main occupation. Although few villages

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are yet to be electrified, the availability of regular supply in far off places has been a problem and the farmers are unable to derive benefits of electricity. The fast depleting kerosene is used for running agricultural machinery including pumps. In addition, people burn firewood and dung cakes for cooking which damages the ecosystem. The burning of cow dung deprives farmers of the use of potential source of organic manure. Further, owing to reduced energy resources, farmers are unable to process the agricultural products to enable them to accrue more benefits. In rural economy, energy is basically needed for cooking food, heating of water and lighting of houses at the domestic front, while in agricultural sector, energy is required for field operations, pumping water, spraying of insecticides, post-harvest activities and running of agro and cottage industries. The situation is still worse in arid zone where biomass is scarce and no hydroelectricity is available. In addition, farmers are unable to earn money due to lack of energy resources to run appropriate devices in cottage industries. The arid and semi-arid region of the country receive much higher radiation as compared to rest of the country with 6.0 $kWhm^{-2}$ day^{-1} mean annual daily solar radiation received at Jodhpur having 8.9 average sunshine hours a day. Further, it was estimated that solar energy of 1% of land area, wind power of 5% of land area and biogas (80% collection efficiency) can provide 1504 kWh $year^{-1}$ energy per capita in arid region, while the average per capita total energy consumption of India is 1122 kWh $year^{-1}$. In this context, renewable sources of energy like solar energy, wind power and biogas need to be harnessed for the sustainable development in general and catering the farmer requirements in particular.

11.2 Solar PV-Operated Water-Lifting/Pumping System

Water is required for irrigation. The demand for irrigation is increasing day by day. Even in rainfed area, life-saving irrigation is a must. Pressurized irrigation systems, e.g. drippers, sprinklers, etc., are of great importance in 'crop per drop' mission; however, ensured power supply is essential to operate these systems. PV pumping solar systems may be quite helpful in running pressurized irrigation system. Specifically, solar pumps may be useful as water-lifting devices in irrigation canals and also to evenly distribute water in command areas and thus will reduce the wastage of water. At present, about 16 million electric pumps and 7 million diesel pumps are in operations in India for irrigation purpose; however, they are highly energy intensive and therefore if replaced with solar pumps may greatly contribute to country's energy security. Till December 2018, 1.96 lakhs pumps were installed in India, mostly of 2 or 3 HP pumping system, which has been recently appended with 5 HP pumping system. These solar pumps have the capacity to withdraw water from 75 m depth and therefore may be beneficial in region where groundwater is not deeper than it. Moreover, solar pumps are directly operated by solar irradiance, and therefore diurnal and seasonal variations of it play a key role in implementation of solar PV pumps in a place. Solar photovoltaic (PV) pumps are quite useful for irrigating the crops using solar energy. Solar PV pumps can be best used with pressurized irrigation system, e.g. drippers, sprinkler, etc. Small-sized solar PV pumps of 1 HP

Fig. 11.1 Solar PV pumping system: (**a**) 1 HP AC pump and (**b**) 1 HP DC pump. (Source: CAZRI Annual Report 2013–14, pp. 89–90)

capacity are suitable to irrigate crops from surface water reservoir in greenhouses, poly houses and shade net houses for high-value vegetable production. It has been observed in field that 1 HP capacity solar pumps with 3–4 m suction head generates a pressure of about 2–2.5 kg cm^{-2} which can operate 9 mini-sprinklers, 50 micro-sprinklers and drippers. Pressure-discharge relationship of 1 HP solar pump showed a discharge of 45–50 litres per minute when connected to 9 mini-sprinklers (Fig. 11.1). Solar PV pumping systems have been viewed as viable option for future energy-secured agriculture. Apart from solar PV, pumping system has low life cycle cost, reduces CO_2 emission by 1350 kg CO2 $year^{-1}$ m^{-2} panel area and increases crop yield and can also generate electricity when not in use (Santra et al. 2017). Solar PV pumping system may be used in far remote locations, where electric grids are not available. Considering low LCC and above said benefits, solar PV pumping system will obviously be considered as the first choice by farmers to irrigate crops.

11.3 Solar PV-Operated Equipment for Plant Protection

Three solar PV-operated equipment are very useful for uniform spraying, and dusting of plant protection chemicals is very important for effective control of pest and diseases. Solar PV sprayer is used for spraying of agricultural chemicals in agricultural field. To provide energy to DC pump (60 W) of the PV sprayer, 120 W_p capacity (60 W_p × 2 Nos) solar PV modules are connected so that the produced energy may be directly used by DC motor. To provide continuous supply of power to the system and other uses, a provision of battery bank (two batteries 12 V, 7 Ah each) is made. Performance of the solar PV sprayer showed an application rate of 84 litre h^{-1} and coverage of 0.21 ha h^{-1}. The application rate varied as per the availability of solar irradiation, e.g. during 10:00 am to 11:00 am in a clear winter day at Jodhpur, the application rate was 82.2 litre h^{-1}, whereas during 12:00–1:00 pm, it was 90.2 litre h^{-1}. The capacity of the tank used in the sprayer was 30 litre, and with one filling, the sprayer can cover an area of about 25 m × 25 m (Fig. 11.2). The approximate cost of the solar PV sprayer is INR 25,000/-.

Fig. 11.2 Solar PV sprayer. (Source: CAZRI Annual Report 2016–17, pp. 98–100)

Solar PV duster is used for application of dust formulation pesticides, e.g. sulphur dust, malathion powder, etc. It essentially comprises a PV module (7.5 W_p), a metal carrier, storage battery (12 V, 7 Ah) and especially designed compatible dusting unit. The PV module is carried over the head with the help of a light metal carrier made of aluminium sheet, which provides shade to the worker and simultaneously charges the battery to run the duster (Pande 1998). The battery is stacked in a bracket, which is fixed in situ to the panel carrier. The field capacity of the device is about 0.075 ha h^{-1}. The unit has also the additional facility for lighting purpose during night time (Fig. 11.3). Approximate cost of this device is about INR 9000/– (Poonia et al. 2018a, b).

11.4 Solar Dryer for Drying Agricultural Produces

Non-availability of adequate irrigation water and harsh climatic condition, generally prevailing in Thar desert of India, force the farmer not to grow fruits and vegetables on large scale. As a result, the community in the region largely depends on tree-/bush-based non-conventional and locally available fruits and vegetables, viz. “Kumtia” (*Acacia senegal*), “Sangri” (*Prosopis cineraria*), “Gunda” (*Cordia myxa*), “Pilu” (*Salvadora oleoides*), “ker fruits” (*Capparis decidua*), etc. These products are either consumed as fresh with little primary processing and/or after drying. The vegetable “punchkuta” is prepared using these above tree-/bush-based dried vegetables and is one of the well-known preparations generally served in star hotels and on certain specific occasions in the region. In last one decade or so, a drastic change has

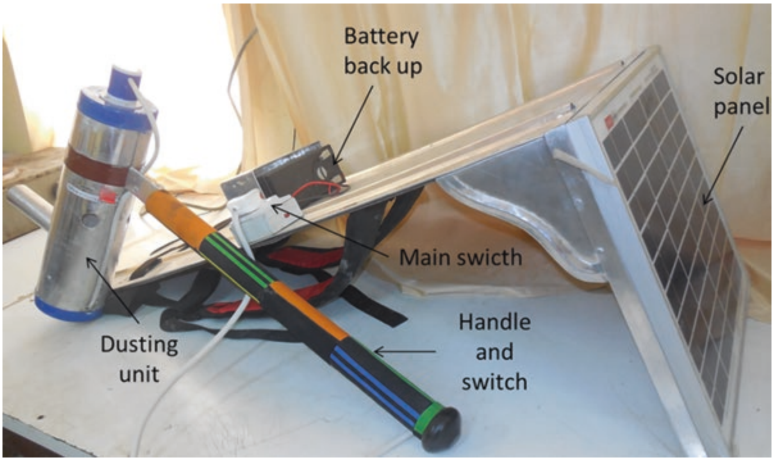

Fig. 11.3 Solar PV duster. (Source: Pande 1998)

occurred with respect to increased consumption of conventional vegetables in the area. This has happened due to the import of these conventional vegetables from other states to the state of Rajasthan, particularly western part. Due to this change and local market demand, the farmers of the region have started cultivation of vegetables with their limited irrigation water resources. However, the community in the region still has a choice to consume dry fruits and vegetables. The supply of these items from neighbouring states as well as local production causes seasonal glut in the market. Fruits and vegetables, if dried, can be stored for a longer duration after drying, and it enables farmers to accrue higher benefits by selling the dried material in off-season. Arid zones have low humidity and high irradiance, and this makes the region most appropriate to use solar energy for drying fruits and vegetables. Solar dryer is a convenient device to dehydrate fruit, vegetables and industrial chemicals faster and efficiently with elimination of problems associated with open courtyard drying like dust contamination, insect infestation and spoilage due to rains (Nahar 2009). Among solar dryers like forced, natural, tilted and domestic type, CAZRI-designed solar dryers, a low-cost tilted type solar dryer, costing about INR 9000 per m^2, have been extensively tested for drying onion, okra, carrot, garlic, tomato, chillies, ber, date, spinach, coriander, salt-coated amla, etc. (Fig. 11.4) (Thanvi and Pande, 1990). The powdered products from some of these solar-dried materials have been tested for instant use. Local entrepreneurs have adopted such inclined solar dryers of variable capacities (10–100 kg). One can save about 290–300kWh/m^2 equivalent energy annually by the use of such dryers, and farmers can accrue higher benefits from solar-dried products (Poonia et al. 2017a, b and 2018a, b). The use of the dryer would result in the reduction of the release of 1127 kg of CO_2 savings/year. Solar-dried vegetables will be more acceptable in the world market and farmers will get more income.

Fig. 11.4 Solar dryer. (Source: Thanvi and Pande 1990)

11.5 PV Winnower-Cum-Solar Dryer for Winnowing and Drying of Food Produces

Winnowing and drying are two important post-harvest applications, which require attention. The villagers face difficulty in cleaning the threshed material if there is lull in natural winds, generally used for this purpose. Generally, in rural areas, small farm holders thresh the material and then carry out the winnowing by pouring down the threshed material, which is kept on the locally available tray at a height with stretched hands. When the tray is shaken, the material falls down, and if there is natural wind, it blows away the lighter particles and grain falls down. In the absence of natural winds, the farmers are handicapped, and as electrical supply is intermittent, they have to wait for the wind. The PV winnower-cum-dryer has been used for winnowing threshed materials in the absence of erratic and unreliable natural winds and also for dehydrating fruits and vegetables more effectively and efficiently (Fig. 11.5) (Pande et al. 2008). About 35–50 kg grain could be separated within 1–1.5 h from threshed materials of pearl millet, mustard grain and cluster bean (Fig. 11.6) (Pande 2003). The same fan of winnower is used in a dryer to use the system for dehydrating fruits and vegetables under forced circulation of air. A solar PV dryer dries 40–50 kg of fruits and vegetables, viz. water melon flakes, kachara (local cucumber) slices, grated carrot, mint, spinach, onion, mushroom, ber, coriander leaves, chilies, etc., and these could be dehydrated in less than half of the time required in open sun drying while retaining its colour and aroma (Pande 2006). Thus, it becomes more useful for domestic lighting and for agricultural purposes such as winnowing and cleaning of grains and dehydrating fruits and vegetables enabling farmer to get more benefits from the same system.

Fig. 11.5 PV winnower-cum-solar dryer. (Source: Pande 2006)

Fig. 11.6 Winnowing of cluster bean (Guar). (Source: Pande 2003)

11.6 Animal Feed Solar Cooker for Milch Animals

In the arid region of Rajasthan, animal husbandry contributes a major portion of the income of rural people. Livestock provides a range of benefits to rural people, e.g. provides nutritious milk for domestic use, helps in income generation through sale of milk in local markets, provides manures to maintain soil fertility, etc. Thus, it plays a major role in generating employment and reducing poverty in rural areas. Apart from it, livestocks are commonly used for draft power in farm operations.

Fig. 11.7 Solar cooker for animal feed with reflector. (Source: Nahar 1994)

However, these benefits can be availed if digestive and nutritive feeds are given to these livestock animals. Boiling the animal feed helps in improvement of digestive and nutritional quality of the feed which in turn improves both the milk quality and quantity. Therefore, rural people in arid western Rajasthan generally boil the animal feed daily before giving it to livestocks. Firewood, cow dung cake and agricultural wastes are commonly used for boiling purpose. This traditional practice does not ensure the quality feed because it requires slow cooking. Solar cooking is the most suitable option to prepare the animal feed. Moreover, drudgery involved in conventional boiling process can also be avoided in solar cooking, and it also saves fuel wood. Therefore, a low-cost high-capacity solar cooker has been designed for boiling of animal feed using solar energy (Nahar 1994). The animal feed solar cooker was fabricated using locally available materials, e.g. clay, pearl millet husk and animal dung (Fig. 11.7). About 10 kg of animal feed can be boiled in a single animal feed solar cooker per day. The performance of the animal feed solar cooker can be improved by providing an additional reflector during extreme cold days. Crushed barley (*Jau Ghat*), *guar korma* and *gram churi* with water can be successfully boiled using the animal feed solar cooker between 9:00 AM and 3:00 PM. Animal feeds, viz. cotton seed and *khal*, have also been successfully boiled by farmers using the animal feed solar cooker. The solar cooker saves time of farm women and 1059 kg of fuel wood is saved per year which is equivalent to 3611 MJ of energy (Nahar et al. 1996). It is easy to fabricate at village level at a cost of about Rs. 9000 per piece for carpenter who will get job for the fabrication of glass frame which is also very simple. Conservation of firewood helps in preserving the ecosystem, and animal dung cake could be used as fertilizer, which will enhance agricultural productivity. This will reduce CO_2 emission and reduce drudgery. Moreover, solar cooker will reduce 1442.64 kg of CO_2/year and increase farming income if used on regular basis.

11.6.1 Thermal Performance and Testing of Solar Cooker for Animal Feed

The thermal performance of animal feed solar cooker has been carried out according to the Bureau of Indian Standards (BIS) and American Society of Agricultural Engineers Standard (ASAE). Its first figure of merit (F_1), second figure of merit (F_2) and standardized cooking power (P_s) were found as 0.089 m^2 °C /W, 0.288 and 27.40 W, which indicate that the developed cooker falls under category "B", as per standard ($F_1 > 0.12$, class A cooker, and $F_1 < 0.12$, class B cooker) (Poonia et al. 2017a, b). The thermal efficiency of the animal feed solar cooker was 26.4%. The maximum stagnation temperature recorded was 112 °C. It can boil about 10 kg animal feed per day and has the potential of saving about 1000 kg fuel wood annually. The cost of animal feed cooker is Rs. 9500/− without reflector and Rs. 12,500/− with reflector. The present animal feed solar cooker has shown the best performance and highest efficiency for the maximum load. This cooker would save about 1000 kg of fuel wood annually and provide boiled feed to milch animals. It has been found very suitable as it leads to drudgery reduction involved in traditional cooking using firewood.

11.7 Solar Wax Melter for Making Candles

The solar candle device is based on the principle of flat plate solar collector and greenhouse effect. The solar radiation falls on the transparent glass sheet and enters the collector and gets converted into long-wave thermal radiations, which is not transparent to glass surface, and thus these get trapped inside and increase the inside temperature to a great extent. However, the tilt of the wax melter has to be set according to the seasonal variation of tilt angle, which is given as,

$$\text{Declination angle} = 23.45\left[360\left(284+n\right)/365\right]$$

where n = number of days of the year, January 1, being the first day of the year.

$$\text{Tilt angle} = \text{latitude} \pm \text{declination angle}.$$

The tilt remains equal to latitude (26.18 degree for Jodhpur) on March 21 and September 23. The average tilt angle for 12 months is given in Table 11.1.

The conventional methods of preparing candles from wax are unhygienic, need attendance during wax melting process and also suffer from many other drawbacks. The solar method is quite safe and convenient and obviates any type of care or attendance during intermediate melting process of raw materials. Operation and maintenance of the solar candle device is easy. The working of the device for production of candle is simple. It needs no extra space and can be operated in the house itself or in the field. One-time attention is sufficient for daily production of candles/wax lamps by solar candle device. The paraffin wax is loaded once a day in the solar machine and then the machine is left intact. The melting process takes place in the

Table 11.1 Average tilt angle for different months of the year

S. No	Day of month	Tilt angle
1	January 15	48.45
2	February15	39.80
3	March 16	28.60
4	April 15	16.77
5	May 15	7.39
6	June 14	2.87
7	July 14	4.66
8	August 13	10.85
9	September 12	21.96
10	October 12	33.90
11	November 11	44.09
12	December 11	48.15

Fig. 11.8 Solar wax melting device (Source: Chaurasia, 1991)

solar machine during the day and the melted material is collected from it for candles or wax lamps production in the evening. The time period of 2–3 h in the evening is sufficient for the candle production. The candle production from a small unit of solar machine is 10–16 kg day^{-1} during summer season and 6–9 kg day^{-1} during winter season (Fig. 11.8) (Chaurasia et al. 1983; Chaurasia 1991).

The dimensions of the wax melter are as given below:

Absorbing area – 0.5 m^2.
Loading capacity – 18 kg wax.
Total dimensions – 106 × 75 × 20 cm.
The cost of the wax melter including mould comes to about INR 12000/−.

11.8 Solar Desalination Device

Water is a basic necessity of man along with food and air; the importance of supplying hygienic potable/fresh water (less than 500 ppm of salt) can hardly be overstressed. Large number of people in many countries are lacking fresh drinking water (WHO 2013). As far as drinking water is concerned, it is scarcely available in western arid region of India and people depend on rain water collected from rooftop, which is too little to meet their drinking water demand. The impact of waterborne infectious diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. Generally, in summer season, villagers travel many miles in search of fresh water. It is observed that at least one or two family members are always busy in bringing fresh water from distant sources. The worst conditions are generated if the resources of water are not available and villagers are forced to take highly saline underground water containing nitrate and fluorides or contaminated with pathogenic microbes' pond water (Arjunan et al. 2009). Fortunately, India is blessed with abundant solar radiation. In arid part of Rajasthan, India, solar irradiations are available in abundance and almost 300 clear sky days are observed. Amount of solar irradiation received in the region is about 7600–8000 MJm^{-2} per annum, whereas in semi-arid region it is about 7200–7600 MJm^{-2} per annum and in hilly areas it is about 6000 MJm^{-2} per annum (Pande et al. 2009).

Solar desalination devices made of cement-concrete, cement hollow block, vermiculite-cement, brick and stone masonry and plastered with cement have been designed, developed and constructed. These are basin-type solar stills made of different types of building/construction materials. The condensing cover of 3.5 mm thickness is made of plane glass which has been placed over the basin of solar still. The inclination of condensing cover for solar still is 20° from the horizontal. The absorber area of each device is 4.2 m^2. The bottom surface of the still was painted with epoxy enamel black to have high absorptivity of solar radiation and resistance to salt and heat. The longer dimension of the device is in the east west direction so as to collect more solar radiation. The output from the solar desalination unit is collected into two distillate channels provided at lower side and is taken out through a pipe into a cylinder (Fig. 11.9). These devices provide distillate output of about 2 lpd m^{-2} with 28–30% efficiency. The solar desalination device can provide 20 litres of potable water (180 ppm TDS) by mixing solar water with desalinated water (5 TDS). The solar desalination unit will overcome the problem of corrosion associated with metallic solar still. In addition, there is a wide-scale adoption of distilled water in dispensaries, laboratories, batteries, etc. It will provide potable water in area with saline groundwater (Singh et al. 2019).

11.9 Passive Cool Chamber for Safe Storage of Perishables

In India, the deterioration of the quality of fruits and vegetables starts immediately after harvest due to lack of farm storage. India is the second largest producer of fruits and vegetables in the world after Brazil and China. Total production of fruits

Fig. 11.9 Solar desalination devices made of vermiculite-cement material. (Source: CAZRI Annual Report 2013–14, pp. 87)

and vegetables in India is about 256.10 million tonnes of which 86.60 million tonnes and 169.50 million tonnes are fruits and vegetables, respectively. Storage of fresh horticultural produce after harvest is one of the most pressing problems of tropical countries like India. Due to high moisture content, fruits and vegetables have very short life and are liable to spoil. Moreover, transpiration, respiration and ripening processes are continued in fruits and vegetables even after harvest. Thus, the deterioration rate increases due to ripening, senescence and unfavourable environmental factors. Hence, preserving fruits and vegetables in their fresh form is required to restrict chemical, biochemical and physiological changes to a minimum level and may be achieved through controlling temperature and humidity (Basediya et al. 2013). Due to highly perishable nature, about 20–30% of total fruit production and 30–35% of total vegetable production in India are wasted during various steps of the post-harvest chain (Arya et al. 2009; Kitinoja et al. 2010; Basediya et al. 2013), and the monetary losses are about Rs 2 lakh crore per annum in India (ASSOCHAM 2017).

In arid region of Rajasthan, the weather conditions, even in normal years, for most part of the year, remain too dry and inhospitable for human and livestock. Prevailing low humidity and high temperature regulates physiological activities of fresh vegetables that affects their physio-chemical characteristics during the storage period. The high ambient temperature accelerates the process of dehydration in fruit and vegetable, which leads to reduction in its water content, decrease in shelf life and consequent spoilage in due course of time. Due to low humidity (13–33%) prevailing in the arid region particularly in summer, the cooling effect based on evaporative cooling principle becomes prominent and effective as it causes high evaporation and therefore results in more depression in temperature. Considering this, a low-cost, eco-friendly and energy-saving new storage system called “zero energy passive cool chamber (ZEPCC)” has been designed and developed at ICAR-CAZRI, Jodhpur (Chaurasia et al. 2005). This system is based on evaporative cooling option for preservation and enhancing shelf life of fruits and vegetables without using any active source of energy. The passive cool chamber is based on the principle of evaporation. Evaporation is the process of changing liquid phase into gaseous phase at a temperature below its boiling point.

11.9.1 Design and Construction of Improved Zero Energy Passive Cool Chamber

The design of passive cool chamber has been improved by increasing the evaporating area, and it is installed in the solar energy yard of CAZRI, Jodhpur. It consists of a double-walled system having inner and outer chambers made of baked bricks as shown in schematic diagram (Fig. 11.10). In both the chambers bricks are stacked in vertical walls and have been joined together with cement-sand in the ratio of 1:10. The inner chamber is surrounded by outer chamber and coarse sand is filled between the two. The dimensions of both chambers are 1200 mm × 1200 mm (outer chamber) and 800 mm × 800 mm (inner chamber). The heights of the chambers are 730 mm (outer chamber) and 420 mm (inner chambers). The water is also filled between inner and outer chamber. The baked bricks of cool chambers are porous enough and water filled between the cool chamber's seeps through it. The water seeping through walls of outer chamber evaporates and consequently reduces the temperature of the cool chamber. The holes have been bored in both chambers by using drilling machine. In the outer chamber, 40 holes (dia 1.5 cm, depth 40 cm) have been bored and the distances between these holes are 12 cm. In the inner chamber, 28 holes have been bored (dia 1.5 cm, depth 20 cm) with a distance of 11.5 cm

Fig. 11.10 Improved zero energy passive cool chamber for preservation of vegetables. (Source: Chaurasia et al. 2005)

between the holes. These holes have increased the evaporating area of the cool chamber for fast cooling. Provisions have also been made for water evaporation from the bottom side of the cool chamber by providing suitable channels which further enhances temperature reduction and maintains high humidity in the chamber. The water filled up in the annular side walls helps to maintain high humidity inside the inner chamber and reduces temperature. To cut off solar insolation, a slanting shed (3250 mm × 3000 mm) has been fabricated. The improved passive cool chamber was found to achieve maximum depression in temperature in 1 h compared to 2–3 h by old chamber. About 13–35 litres of water is required daily in the cool chamber to keep the walls wet depending upon the season and the climatic conditions of the day (10–25 litres of water in winter and 18–38 litres in summer). Kitchen or wastewater may also be used. About 2–3 litres of water is sprinkled on the cotton cloth provided on the top side of the lid of the cool chamber to conserve moisture that maintains high humidity inside the cooling area.

11.9.2 Performance of Zero Energy Passive Cool Chamber

The improved cool chamber is able to reduce the inside temperature by about 12–14 °C during summer and 6–8 °C during winter and maintains humidity more than 90%, to preserve vegetables for short-term period. It can safely preserve vegetables for 7 days during winter and 4–5 days during summer. The design of passive cool chamber has been improved by holes bored in outer and inner chamber. These holes have increased the evaporating area of the cool chamber for fast cooling. Provisions have also been made for water evaporation and air circulation facility from its bottom giving better results for preservation of vegetables. It successfully prolongs shelf life of vegetables and reduces weight loss and shrinkage and retains freshness of vegetables compared to vegetables preserved inside the room for a short-term period. It can safely preserve vegetables for 7 days during winter and 4–5 days during summer. The improved zero energy passive cool chamber has wide utility for on-farm storage (in remote areas), vegetable markets (away from cities), retailers (vegetables vendors) and in rural areas of arid region. The cool chambers can be easily fabricated by an unskilled person with locally available materials in remote areas/villages/rural homes as per requirement ranging from domestic use (20 kg) to commercial level (1000 kg) (Singh et al. 2017). The above device is very useful to the farmers as well as entrepreneurs for supplementing their income. They can install these devices for enhancing shelf-life of vegetables and preserve them during transit storage for further use or onward sale. The cool chamber is recommended for preservation of vegetables for on-farm storage/vegetables markets for a period of 2–3 days. The vegetables stored in cool chamber, on commercial basis, for this duration remain as good as fresh and fetch good market value. For domestic purpose, the cool chamber, besides prolonging shelf life of vegetables, can also be used for preservation of left-over food materials including milk and its by-products. It can go a long way to prevent spoilage of vegetables due to lack of proper storage facilities besides saving electricity which otherwise is required for this purpose.

11.10 Agri-voltaic System to Enhance Land Productivity and Income

Food and energy are two basic requirements for human civilization. Therefore, competition for land may arise in the future for agricultural use and PV-based electricity generation. There is possibility that solar PV-based electricity production will be preferred over agriculture because of higher efficiency of photovoltaic process (~15%) than photosynthetic process (~3%) specifically in those areas where solar irradiation is available in abundance; however, land productivity potential is low. However, food is the basic need for survival of human being. Therefore, it is thought of producing both simultaneously from a single land unit through agri-voltaic system. Agri-voltaic system produces food and generates PV-based electric energy from a single land unit. Both the processes of photosynthesis for food production and photovoltaic for electricity generation require solar irradiation and land resources as basic requirement. Therefore, in agri-voltaic system, crops are cultivated in between PV arrays and below PV installations for simultaneous generation of food and energy (Santra et al. 2017, 2018).

11.10.1 Crop Production in Agri-voltaic System

Solar PV modules when installed in field, a space between two rows of PV array, need to be kept blank so as to avoid shades of one PV array on another. The interspace area is generally kept as 6 m between two PV arrays when two rows of PV modules are adjusted in an array and ground clearance of PV module is kept as 0.5 m. Similar to this design criteria, the interspace area is of 3 m and 9 m width strip when the PV array is consisted of one row and three rows of PV module, respectively. Therefore, the interspace area between PV arrays is used for cultivation of crops. However, crops should be selected in such a way that it should not affect the PV generation by creating shade on PV module. Moreover, low water requirement and certain degree of shade tolerance of crops may be additional requirements while selecting the crops for agri-voltaic system. About 49% area of agri-voltaic system is available as interspace area for cultivation of crops. Apart from interspace area, the area below PV module can also be utilized to grow suitable crops.

In arid western Rajasthan and Gujarat, suitable crops for interspace area may be mung bean (*Vigna radiata*), moth bean (*Vigna aconitifolia*) and cluster bean (*Cyamopsis tetragonoloba*) during kharif season, whereas cumin (*Cuminum cyminum*), isabgol (*Plantago ovata*) and chick pea (*Cicer arietinum*) during rabi season. Apart from these arable crops, medicinal plants, e.g. gwarpatha (*Aloe vera*), sonamukhi (*Cassia angustifolia*) and shankhpuspi (*Convolvulus pluricaulis*), may be grown in interspace area. Examples of growing isabgol and aloe vera at interspace area of agri-voltaic system are shown in Figs. 11.11 and 11.12 (Santra et al. 2018).

Fig. 11.11 Isabgol crop at interspace area of agri-voltaic system. (Source: CAZRI Annual Report 2017–18, pp. 101–104)

Fig. 11.12 Aloe vera crop at interspace area of agri-voltaic system. (Source: CAZRI Annual Report 2017–18, pp. 101–104)

Fig. 11.13 Cultivation of spinach below PV module in agri-voltaic system. (Source: CAZRI Annual Report 2017–18, pp. 101–104)

Areas below PV modules may be used to grow vegetables and spices, e.g. onion, garlic, turmeric, cucurbitaceous crops, leafy vegetables, etc. Examples of growing onion and spinach below PV module are shown in Fig. 11.13.

11.10.2 Electricity Generation from Agri-voltaic System

The agri-voltaic system is capable of generating electricity from its PV component as a major output. The electricity generated from the system may be directly supplied to local grid through net metering system. Otherwise, cluster of farmers can use the generated electricity for pumping irrigation water or to operate different post-harvest processing machines and equipment. The amount of PV generation depends on the available solar irradiation. At western Rajasthan and Gujarat, where available solar irradiation is about 5.5–6.0 kWh m^{-2} day^{-1}, the average PV generation from agri-voltaic system is about 4–5 kWh kW_p^{-1} day^{-1}. At other parts of the country, where solar irradiation is about 5–5.5 kWh m^{-2} day^{-1} and the number of cloudy days is about 100–150, average PV generation is about 3–3.5 kWh kW_p^{-1} day^{-1}. An example of PV generation from a 50 kWp agri-voltaic system during winter months at Jodhpur is presented in Fig. 11.14.

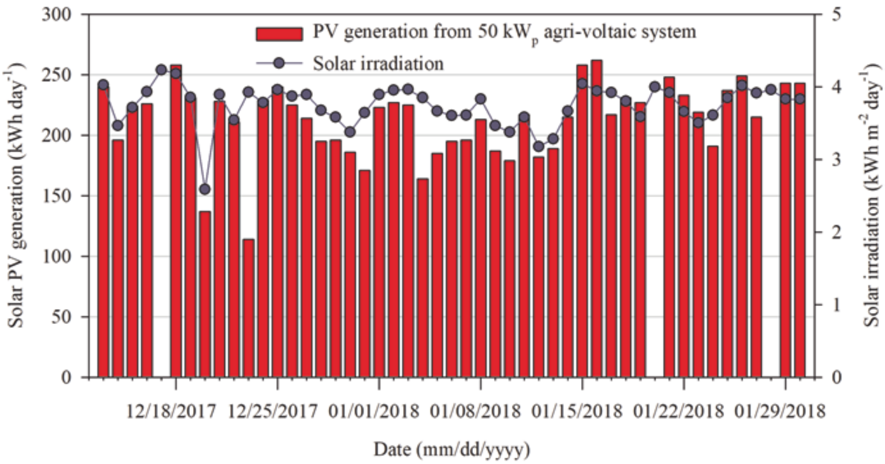

Fig. 11.14 Solar PV generation from 50 kW_p agri-voltaic system at Jodhpur winter months. (Source: CAZRI Annual Report 2017–18, pp. 101–104)

11.10.3 Rainwater Harvesting System in Agri-Voltaic System

For optimum PV generation, regular cleaning of deposited dust from PV module surface is essential and requires about 20–40 litre month^{-1} kW^{-1} of water. The rainwater harvesting system from top surface of PV modules in agri-photovoltaic system has the capability to provide water for cleaning purpose and to recycle it. Apart from cleaning, harvested rainwater may provide irrigation of about 40 mm during rabi season. Potential capacity of harvested rainwater from agri-voltaic system covering 1 ha area is about 3.75–4 lakh litre at Jodhpur.

11.11 Summary

The scope of solar thermal energy in agricultural production and processing sectors is tremendous. It can supplement conventional energy sources to a great extent to make the arid zone more self-dependent on energy. The use of renewable energy will not only curtail the consumption of fast depleting conventional fuels but also reduce greenhouse gas emissions. There is a great need of promoting the solar thermal energy by disseminating these eco-friendly technologies for the sustainable development of society. It requires active participation of users/industrialist and researchers. The availability of clean and green energy source in rural areas would enable farmers to accrue higher monetary benefits through processing and agro-based industries to improve the livelihood of farmers and enhancing their standard of living. The agri-voltaic system has huge potential in farmers' field of the country specifically in those areas where solar irradiation is available in plenty. Installation of such system will produce food as well as generate renewable-based electricity from a single land unit, whereas scarce rain water will be conserved and used efficiently. The agri-voltaic system has capacity to increase farmers' income in a fragile ecosystem. There is scope of improving the land equivalent ratio up to 1.42 by installation of agri-photovoltaic system. The solar PV and thermal devices will be very useful in increasing crop production, processed product and milk production in addition to supplementing conventional energy sources. These devices will ensure increased farmer's income by carrying out integrated activities. Last but not the least these will reduce CO_2 emission to a great extent.

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Conceptual Framework to Social Life Cycle Assessment of e-Waste Management: A Case Study in the City of Rio de Janeiro

12

Leonardo Mangia Rodrigues, Ana Carolina Maia Angelo, and Lino Guimarães Marujo

Abstract

Opposing the problems generated by the negative impacts of industrial production, the corporations, on behalf of minimizing the impacting branches of its reality, over the last four decades, are trying to incorporate frameworks focused on the appliance of the sustainability on its processes. During the last 20 years, a small but growing portion of companies is volunteering to attach social and environmental issues to its business models. One of the major recent issues on production management is about the generated waste, post-consumption matters, and aspects of the reverse logistics, in other words a framework of solid waste management that covers the products' end-of-life. On developing countries, these models are only on its initial phase. There is no regulatory concern on the topic and no economic incentives, and the people who collect this kind of material do not have any instruction on how to do it, regarding its risks to health, safety, and the environment. Setting off on the recognition of the system's limits and the major actors involved on its process of solid waste management is a necessity, elaborating the positive and negative social aspects linked to this activity, starting from the product life cycle way of thinking. The purpose of this chapter is to present and analyze the social impacts of the solid waste management specifically regarding the waste electrical and electronic equipment (WEEE), taking the city of Rio de Janeiro as a case study.

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Keywords
Social life cycle assessment · Solid waste management · Waste electrical and electronic equipment

12.1 Context

Not only the environmental crisis but also the social and economic crises arising from the industrialization process are becoming the focus of various discussions of international entities, such as the UN and the World Economic Forum. Due to the negative impact that such crisis brings to the society, numerous work fronts have been created to stop the advancement of this phenomenon that has truly global proportions. In this sense, the sustainable development, the circular economy, the ISO standards, the life cycle thinking (LCT), and its quantitative methodologies are some of the concepts and practices that intent the creation of the critic and reflexive thought about this crisis, such as reducing the impacts of an environmental and social unsustainable production model. In accordance to the well-recognized concept of sustainable development presented in 1987 (WCED 1987), the World Business Council for Sustainable Development (WBCSD) establishes an intrinsic relation between economic growth and environmental protection from the perspective that life quality in the present time depends on recognition of the most basic needs of the human being through environmental heritage (Schmidheiny 1992). In short, the sustainable development concept can be understood as a dynamic interaction between action and apprenticeship that works in the intersection between the economy, society, and the environment.

One of the main recent concerns about the current production model is regarding the generated waste and strategies of post-consumption, where the reverse logistics plays an important role fostering the waste diversion (Kilic et al. 2015; De Souza et al. 2016; Cao et al. 2016; Guarnieri et al. 2016; Caiado et al. 2017; Dias et al. 2018). The reverse logistics contributes to the reduction of landfill waste since it allows the reuse, recycling, and recovery of waste through a closed-loop supply chain, observed in Fig. 12.1.

This chapter briefly presents how the reverse logistics contributes to a closed-loop supply chain based on the life cycle thinking philosophy, as well as its crucial role toward the circular economy by promoting sustainable practices of handling products in their end of life phase, thus a sustainable solid waste management through reuse and recycling strategies. As the environmental benefits of reverse logistics practices are well-recognized (e.g. Xiao et al. 2019; Islam and Huda 2018), it addresses the social impacts of the reverse logistics by taking the Waste Electrical and Electronic Equipment (WEEE) management in Rio de Janeiro as a case study.

With regard to climate change, it is no longer a purely environmental issue, and it is affecting people's life worldwide. In this sense, the need of a resilient economy and society requires holistic strategies of prevention and mitigation of greenhouse gases emissions that go beyond the environmental aspect. Therefore, it is imperative

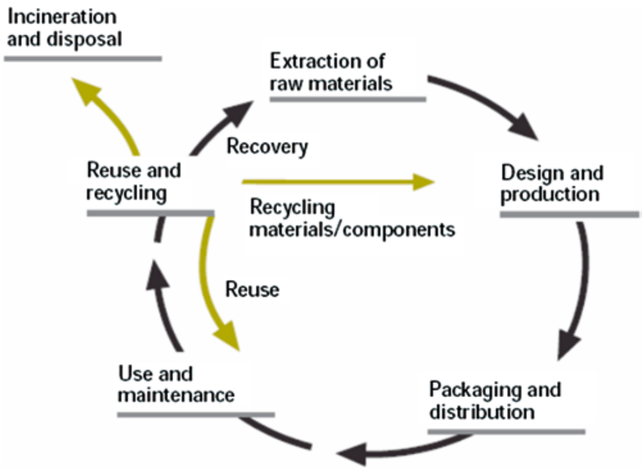

Fig. 12.1 The life cycle of a product and closing the looping. (Source: UNEP 2006)

to consider the multidisciplinary concept of sustainability as a whole in all decisions of various society's dimensions, such as the solid waste management.

12.2 Life Cycle Thinking

As a conceptual approach, life cycle thinking (LCT) is essential in the path to sustainability by closing the looping of the product life cycle (Fig. 12.1), and it is considered a strategic issue to guarantee the sustainable use of natural resources (European Commission 2005, 2008; Manfredi et al. 2011). This approach aims to reduce emissions to the environment as well as to improve the social performance in all life cycle stages.

LCT comprises three well-recognized quantitative methodologies: the (environmental) life cycle assessment (LCA), the social life cycle assessment (SLCA), and the life cycle costing (LCC). All provide the assessment of the sustainable performance of products, services, and processes through the life cycle sustainability assessment (LCSA). A review pointed out LCA as the most used method for evaluating solid waste management systems (SWMS) (Allesch and Brunner 2014). In addition, it was observed a significant increase in the number of publications in this field over the last decade (Laurent et al. 2014).

SLCA, as a social impact decision-making methodology, evaluates the social aspects and potential impacts, negative or positive, along the life cycle of a product or process (Jørgensen 2010). A review carried out by Petti et al. (2016) investigated the methodology of SLCA through case studies and indicated the waste management sector as an important field of application (Moriizumi et al. 2010; Umair et al. 2015; Vinyes et al. 2013).

As mentioned before, SLCA assesses social and socioeconomic impacts found along the life cycle (supply chain, use phase, and the waste disposal). Indeed, the life cycle perspective makes SLCA different from other social impact assessment tools. Social impacts can be understood as negative or positive pressures on the product life cycle stakeholders (UNEP 2009). Among the main stakeholder categories are as follows:

- Workers/employees
- Local community
- Society (regional, national, and global)
- Consumers (covering end-consumers and also the consumers who are part of each step of the supply chain)
- Value chain actors

The assessment of social impact considers all these stakeholders analysing the indicators divided into impact categories, subcategories, and inventory indicators (Fig. 12.2).

Many subcategories can be adopted in the SLCA. A comprehensive set of subcategories is presented in Table 12.1.

SLCA can be conformed to the ISO 14040, the international standard for environment life cycle assessment studies, and thus it can be carried out in four phases: (i) goal and scope definition, (ii) life cycle inventory, (iii) impact assessment, and (iv) interpretation of results.

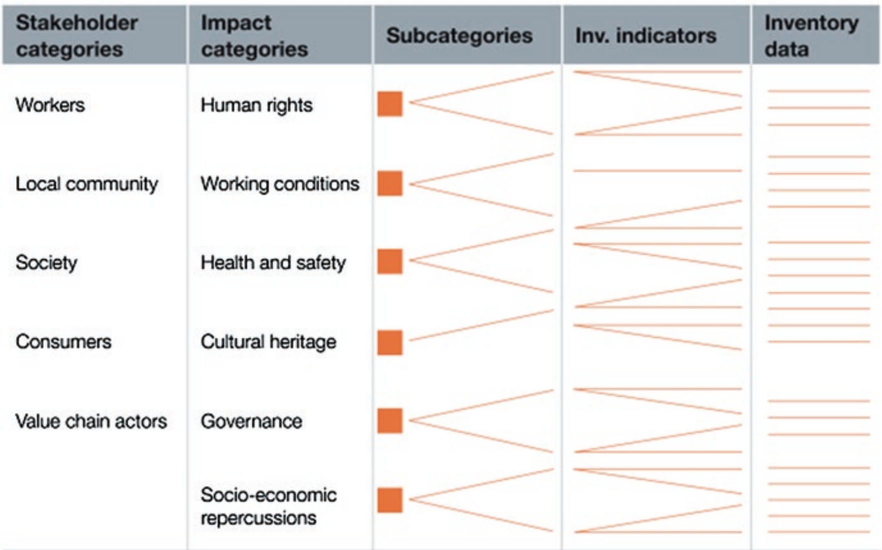

Fig. 12.2 The assessment reference framework. (Source: UNEP 2009)

Table 12.1 Subcategories assessed in SLCA

Stakeholder categories	Subcategories
Worker	Freedom of association and collective bargaining
	Child labour
	Fair salary
	Working hours
	Forced labour
	Equal opportunities/discrimination
	Health and safety
	Social benefits/social security
Consumer	Health & Safety
	Feedback mechanism
	Consumer privacy
	Transparency
	End of life responsibility
Local community/society	Access to material resources
	Access to immaterial resources
	Delocalization and migration
	Cultural heritage
	Safe and healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
	Public commitments to sustainability issues
	Contribution to economic development
	Prevention and mitigation of armed conflicts
	Technology development
	Corruption
Value chain actors	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

The goal and scope definition (phase 1) include a description of the functional unit, as well as the product utility, an overview of the stakeholders concerned, and the system boundary definition. In principle, all life cycle stages should be considered, unless the person commissioned to carry out the assessment justifies the exclusion of one or more life cycle stages that are not relevant from a social or socioeconomic impact viewpoint. As the waste management sector covers the end-of-life phase, SLCAs of solid waste management comprise the assessment of the social impacts from different waste management strategies.

Phase 2 is concerned with the life cycle inventory, where the categories, subcategories, and indicators are defined, including the inventory data collection. In phase 3, an impact assessment is conducted in terms of social impacts on each stakeholder category considered in the study. Finally, the interpretation results (phase 4) provide a judgement of the SCA results based on national requirements and ethical concerns.

12.3 The Social Impacts of Waste Management

The European Commission (Directive 2008/98/EC) has suggested a waste hierarchy that presents a priority on managing solid waste: non-generation, reduction, reutilization/reuse, recycling, solid waste treatment (energy recovery), and environmentally adequate disposal in landfills. Despite the various studies dedicated to analyse the environmental impacts of the solid waste management strategies (e.g. Allesch and Brunner 2014; Bernstad 2012; Srivastava et al. 2015; Angelo et al. 2017), the social impacts of this sector are still incipient.

In developing countries, the solid waste management systems are commonly based on a single disposal option (landfill or even illegal dumping and incineration of wastes), which is operated and managed by local governments in a private-public partnership (PPP). Figure 12.3 shows the typical solid waste management system in developing countries, which encompasses both informal and formal sectors.

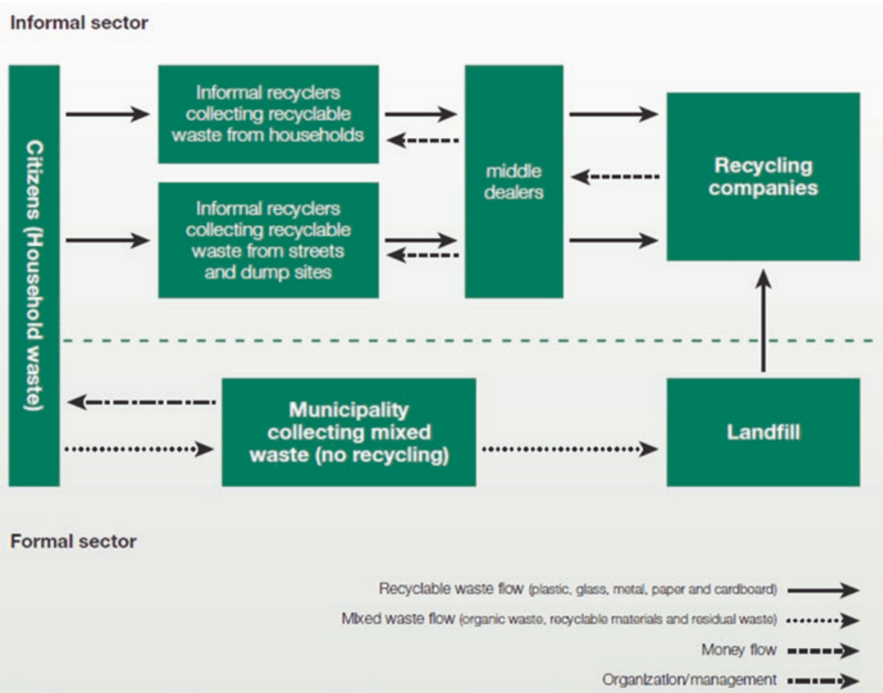

Fig. 12.3 Typical solid waste management system in developing countries. (Source: Aparcana and Hinostroza 2015)

By observing the figure, several stakeholders are involved in solid waste management systems, such as households, commercial establishments, local governments/municipalities, national government, private waste service providers, informal private waste service providers, nongovernmental organizations (NGOs), and external support agencies (Aparcana and Hinostroza 2015).

Especially in low- and middle-income countries, the waste management sector contributes to the informal sector, which comprises a complex recycling chain. The common social problems of the waste management sector are inappropriate safety working conditions, child labour, discrimination, and social rejection (Srivastava et al. 2015). Moreover, the most frequent informal workers comprise those coming from socially vulnerable groups, children, and pregnant women (Aparcana and Salhofer 2013). However, despite these social problems, the informal sector in waste activities contributes significantly to increase the recycling rates in these countries (Aparcana and Hinostroza 2015).

12.4 The SLCA of WEEE

The growing amount of WEEE (waste electrical and electronic equipment) and its improper and unsafe treatment and disposal pose significant risks to the environment and the human health. WEEE, also known as e-waste, comprises a wide range of products, including almost any household or business item with circuitry or electrical components with power or battery supply, classified into six waste categories (Baldé et al. 2017) (Table 12.2).

Table 12.2 WEEE categories

Category	Description
Temperature exchange equipment	More commonly referred to as cooling and freezing equipment Typical equipment includes refrigerators, freezers, air conditioners, and heat pumps
Screens/monitors	Typical equipment includes televisions, monitors, laptops, notebooks, and tablets
Lamps	Typical equipment includes fluorescent lamps, LED lamps, and high-intensity discharge lamps
Large equipment	Typical equipment includes washing machines, clothes dryers, large printing machines, dish-washing machines, electric stoves, copying equipment, and photovoltaic panels
Small equipment	Typical equipment includes vacuum cleaners, microwaves, electric shavers, toasters, electric kettles, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, ventilation equipment, small medical devices, and small monitoring and control instruments
Small IT and telecommunication equipment	Typical equipment includes mobile phones, pocket calculators, global positioning systems (GPS), personal computers, routers, and printers

Source: Adapted from Baldé et al. 2017

Each product of the six categories described above has its own life cycle and lifespan, which requires different reverse logistics schemas and recycling processes. Because of this situation, many designs of reverse logistics for WEEE were created, mostly in developing countries, respecting the particularities from each area, trying to contain the social and environmental impacts that these activities generate.

In developing countries, the reverse logistics of WEEE are still in the beginning of the whole process of implementation; because their legislation is void from this subject, there are no economic boosters, and the waste pickers have almost no knowledge to deal with the risks regarding health, security, and environmental protection (Schluep et al. 2009).

Schluep and co-authors stated that Brazil is one of few South America countries that have the structure to maintain a reverse logistics chain of WEEE. The Brazilian National Policy on Solid Waste (PNRS), implemented in 2010, represents a huge step regarding WEEE management and brings an innovative approach among the developing countries about the WEEE reverse logistic chain (Demajorovic et al. 2016). The life cycle of the EEE (electrical and electronic equipment) into waste and the most common WEEE management are presented in Fig. 12.4.

12.4.1 Case Study: SLCA of WEEE in the City of Rio de Janeiro

This case study aims to create a conception board, which defines the stakeholders, impact categories and subcategories, and, furthermore, SLCA indicators taking into account the reverse logistics of WEEE in the city of Rio de Janeiro. The city of Rio de Janeiro was chosen because of the ease of access to the cooperatives, the data for modelling the system in a megacity with almost 12 million of people, the relevance of the city in the Brazilian context (second in GDP), the research laboratory being located in the same city as well as for the year 2014, and the estimated generation of waste electrical and electronic equipment for the city of Rio de Janeiro being 44.261 (tonne/year), the highest in the state of Rio de Janeiro (OTTONI 2018). It represents a significant contribution with theoretical basis for practical applications in the WEEE area, which is a starter sector in the use of SLCA. The system modelling bases on different methodologies of S-LCA were found in two case studies concerning methodological approach applied to social impact assessment: one in the recycling sector of developing countries (Aparcana and Salhofer 2013) and the other in the informal sector of WEEE recycling in Pakistan (Umair et al. 2015). The function unit adopted refers to the 1-year amount of e-waste generated per person in the city of Rio de Janeiro.

12.4.1.1 Methodology

The study follows three steps: (i) planning and definition, (ii) development, and (iii) analysis and conclusion. In the planning and definition step, a literature review searched the main scientific databases using the ‘SLCA or social life cycle assessment’ as the search string for paper topics (title, abstract, and keywords). In order to cover Brazilian studies, a search on national databases was also carried out.

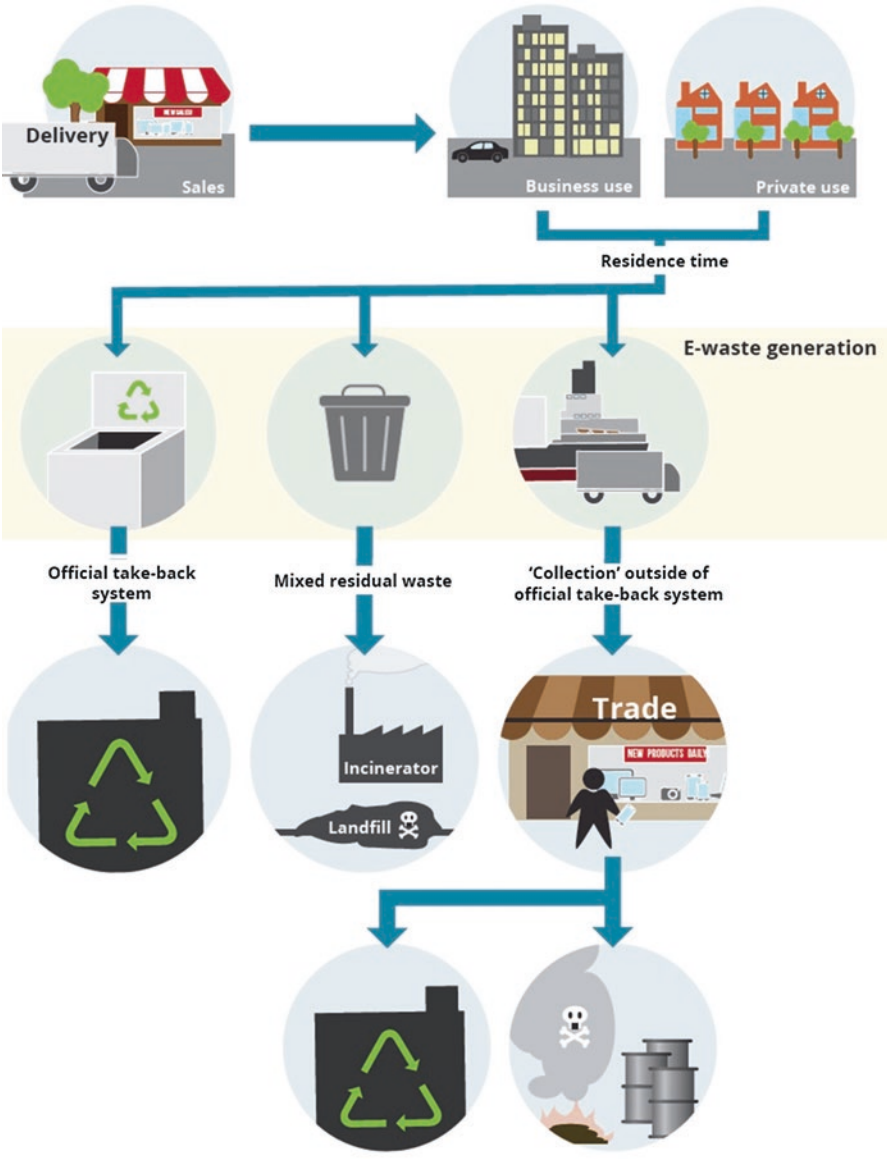

Fig. 12.4 The life cycle of EEE into waste. (Source: Baldé et al. 2017)

In the development phase, the main aspects regarding the scope of the SLCA were addressed, such as the description of the geographical area, the system boundary delimitation, as well as the cut-offs adopted. Stakeholder interviews were conducted in order to map the process of the reverse logistics and its operations in the case study analysed. Finally, in the conclusion phase, the categories, subcategories, and indicators took from the stakeholders were put into the same framework to assess the social impacts.

12.4.1.1.1 The System Modelling

The main goal of this study is the identification of the socioeconomic impact subcategories and the definition of inventory indicators related to the five categories of stakeholders proposed by UNEP (2009) and enrolled in the e-waste's life cycle in the city of Rio de Janeiro. Information from three recycling cooperatives (Coops A, B, and C) were collected through onsite visits, mainly aspects regarding the health and security of the work environment and the comprehension of the social context that this activity is.

In first visit to Coop A, it understood that due to the fact that its headquarters is very near to a drug-selling area, the study could not continue in face of security reasons. Coop B, even though near a slum, was where most of data research was found. The management is well trained, considering it participates in projects with universities and private companies. Coop C, bypassing its locality, is similar to Coop B regarding the level of development, since both cooperatives work together in an academic project. During the visits and interviews, two recycling companies that bought WEEE from the cooperatives were identified – Companies X and Y.

Company X only buys WEEE from the category 'temperature exchange equipment', and because of the economic crisis faced by the country, it had to retreat from this particular market due to financial problems. Company Y, located near a slums complex, is a very large company with 12 units located in Brazil, and it is present also in South America, the USA, Israel, and Japan. It is responsible for the purchase of all the higher worth materials separated in the screening process of the e-waste from Coop B and Coop C. All the activities performed in the modelling system by the cooperatives and the recycling companies are in accordance to legal requirements.

As the object of the study is the WEEE of small IT and telecommunication equipment, the system boundary assessed covers the processes related to the reverse logistics and treatment of the waste collected. Therefore, the life cycle stages related to the EEE manufacturing, distribution, and consumption are not considered in this assessment. The recovery of low-added materials from the WEEE such as glass and plastics was also excluded from the study considering it requires specific recycling process.

12.4.1.1.2 The Process Description

The four processes considered in this assessment are shown in Fig. 12.5. The cooperative is responsible for the collection and transportation of WEEE. The sorting refers to the process where the waste is separated into different elements. Materials

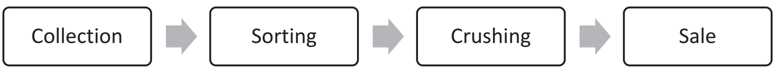

Fig. 12.5 Processes evaluated

with high potential added value (e.g. components, battery, screens, precious metals) are sold to electronic recycling companies, and those with low added value (e.g. glass, plastic, metals such as copper) are sold to the scrapyard. The crushing is done mechanically by the recycling companies, which sell or export the materials to be recovered in other countries.

The sorting activity has much more concern regarding the worker's health and security due to the type of work and exposition to chemicals elements. This activity needs preview training, as it is done manually, and the separation of the elements requires certain knowledge. It is remarked that the workforce of the recycling companies is more qualified than the workers of the cooperatives.

12.4.1.1.3 The Stakeholders' Category Definition

According to UNEP (2009), stakeholder is a party that has an interest in an organization and can affect or be affected by the business. The definition of each category resulted from the literature review and the interviews conducted in the study. The stakeholders included in this study are presented in Table 12.3.

12.4.1.1.4 Subcategories, Indicators, and the Social Impacts

For each stakeholder category, subcategories and indicators were taken into account considering the aspects pointed out by the reviewed studies of SLCA, as well as methodological sheets of UNEP (2013) and studies of Aparcana and Salhofer (2013) and Umair et al. (2015).

As the SLCA methodology allows to consider only the impact subcategories that are relevant for the system assessed (Arcese et al. 2017), the social impacts that are not in the system were excluded (e.g. impact on the cultural heritage). One subcategory considered is the workers' education from both cooperative and recycling company. It pointed the relevance of educational level in different activities. Another

Table 12.3 Stakeholders' categories adopted in the study

Stakeholder category	Description
Local community	People who live near where all the processes happen. All the processes phases happen in the city of Rio de Janeiro
Value chain actors	According to the system modelling, these people work mainly in the sorting, crushing and sale/destination. Here are included the cooperatives and the recycling companies of the higher value-added material. The WEEE importers are not included as well as those actors that process other materials like plastic, glass, aluminium, etc.
Consumers	Responsible for the dispose of WEEE. They can be a person or companies
Workers	Comprehend all the workers of all processes assessed. They are divided into two groups (operational and technical). The operational workforce is responsible for the collection, sorting and crushing. The technical workers act in the operations management. They are the president of the cooperative or the manager of the recycling company. Due to the fact that these companies need legal authorization to operate, the social impacts are diminished by this
Society	Includes all population and organizations of the city of Rio de Janeiro

subcategory is the psychological impacts concerning the work environment. The impacts about the job, per say, take into account salary, work hours, and equality in work opportunities, among others. Health and security at work are health policy indicators, also considered in the study.

With regard to the consumers, the system modelling presented by Umair et al. (2015) does not include them, because the authors declared that they are not involved in the WEEE informal recycling process in Pakistan. However, as this study refers to WEEE collected by cooperatives, the consumers are taken into account. Different to Umair et al. (2015), the potential impacts concerning the type of organization, work conditions, and governance were considered since the case study refers to a formal reverse logistics process in the city of Rio de Janeiro.

A total of 19 subcategories and 43 indicators were identified as relevant for the case study assessed. The following Tables 12.4, 12.5, 12.6, 12.7, and 12.8 summarize them.

The stakeholder local community is involved in all the four processes assessed. The impact subcategories of this stakeholder reflect the social impacts generated by the cooperatives and the recycling company. Aspects related to the health strengthening of the community, the diversity of the group, and the percentage of the local community employed locally are some of the indicators. The outcomes of the research in the cooperatives have a slight tendency to be more positive due to the social economic-specific characteristics of their members and because of their business model.

The value chain actors refer to the cooperatives and the WEEE recycling company. Promoting social responsibility and fair competition are the two impact subcategories for this stakeholder. Consumers are considered as stakeholders in two different ways: big consumers, such as big enterprises and organizations, and the small ones, such as individuals. In this sense, health and security information about the discarded products are very important as well as the demonstration of the results of the environment and social impacts.

Workers comprise an important stakeholder category present in all processes assessed. The indicators translate broader social impacts regarding social security, worker health, salary and aspects regarding negotiation, psychological conditions to work, disposition to work, and professional satisfaction. The indicators concerning the potential impacts related to the socioeconomic repercussion in the educational level are the level of education of the recycler's family children, the scholar evasion in their families, and programmes of self-development. Finally, society represents all the population of the city of Rio de Janeiro that is affected, direct or indirect, by the system.

12.5 Final Remarks

The main objective of the case study presented in this chapter is to contribute to the SLCA system modelling, including the proposition of impact categories and subcategories, as well as the creation of a set of indicators to understand the potential

Table 12.4 Subcategories and indicators for the stakeholder category worker

Subcategories	Indicators
Hours of work	Respect of contractual agreements concerning overtime
Child labour	Absence of working children under the legal age
Health and safety	Absence of injuries or accidents
	Presence of a formal policy concerning health and safety
	Vaccination of workers
	Education and training programmes
	Prevention and risk control programmes
	Adequate general occupational safety measures are taken
	Preventive measures and emergency protocols exist regarding pesticide and chemical exposure
	Appropriate protective gear required in all applicable situations
Social benefit/social security	Presence of legal employment contracts
	Social benefits provided to the workers
	Access to social worker programmes
Psychological conditions	Wishing on working at the same company
	Job satisfaction
Forced labour	Birth certificate, passport, identity card, work permit or other original documents belonging to the worker are not retained or kept for safety reasons by the organization neither upon hiring nor during employment
	Workers are free to terminate their employment within the prevailing limits
	Workers are not bonded by debts exceeding legal limits to the employer
	Workers voluntarily agree upon employment terms. Employment contracts stipulate wage, working time, holidays and terms of resignation. Employment contracts are comprehensible to the workers and are kept on file
Fair salary	Average wage
	Presence of suspicious deductions on wages
	Regular and documented payment of workers
	Lowest paid worker, compared to the minimum wage
Equal opportunities/discrimination	Presence of formal policies on equal opportunities
	Ratio of basic salary of men to women by employee category
Education	Presence of educational programmes for empowerment
Freedom of association and collective bargaining	Presence of unions within the organization is adequately supported

social impacts caused by the reverse logistics of WEEE (e-waste). The review of the scientific literature has shown that WEEE recycling process has negative social consequences to the workers, especially regarding their health. Nevertheless, it may have positive impacts concerning the growth in employment rate and education promotion. The need of articulation between society, enterprises, NGOs, and the government is a must, as well as between organized civil society, NGOs, and the

Table 12.5 Subcategories and indicators for the stakeholder category local community

Safe and healthy living conditions	Organization efforts to strengthen community health (e.g. through shared community access to organization health resources)
Community engagement	Diversity of community stakeholder groups that engage with the organization
	Organizational support (volunteer-hours or financial) for community initiatives
	Number and quality of meetings with community stakeholders
Local employment	Percentage of workforce hired locally
	Strength of policies on local hiring preferences

Table 12.6 Subcategories and indicators for the stakeholder category society

Public commitment to sustainability issues	Presence of publicly available documents as promises or agreements on sustainability issues
Contribution to economic development	Engagement of the sector regarding sustainability and economic development

Table 12.7 Subcategories and indicators for the stakeholder category value chain actors

Promoting social responsibility	Presence of explicit code of conduct that protect human rights of workers among suppliers
	Membership in an initiative that promotes social responsibility along the supply chain
Fair competition	National law and regulation
	Sectoral regulation
	Sectoral agreement

Table 12.8 Subcategories and indicators for the stakeholder category consumer

Health and safety	Quality of or number of information/signs on product health and safety
	Quality of labels of health and safety requirements
Transparency	Communication of the results of social and environmental life cycle impact assessment

government so that the PNRS, specifically with regard to WEEE, can be effectively put into practice.

Adequate treatment of WEEE is a potential source of income and profits for those involved in the system, and given the importance and strategic relevance of the treatment of WEEE, government along with all parties involved in the life cycle, from the cradle to grave, should initiate programmes of economic, environmental, and social leveraging for this sector.

For a complete analysis of the WEEE sustainability, life cycle-based studies such as SLCA, LCA, and LCC are further required. Seeing that the social context is a complex issue, it is necessary to build a better and more effective basis in SLCA studies, using a multidisciplinary team and involvement of social scientists.

Considering that SLCA studies are beginning to bloom, the results of this work can contribute to the advancement of this area, once it proposes a structuring model of a life cycle inventory to give the diagnosis of WEEE management in the city of Rio de Janeiro.

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Unsustainable Management of Plastic Wastes in India: A Threat to Global Warming and Climate Change

13

Amit Vishwakarma

Abstract

First rural to urbanization and now urbanization to smart cities, sign of development also raises some issue of unsustainable approaches of solid wastes and its impact on our ecosystem. The unsustainable solid waste management approaches have adverse impacts on ecosystem and human health. Over 90% of waste were directly thrown in open ground and burned incompletely in low-income countries, and in 2016, 5% of global emissions were generated from solid waste, excluding transportation (World bank, What a waste: an updated look into the future of solid waste management. http://www.worldbank.org/en/topic/urbandevelopment/brief/solid-wastemanagement. Accessed on 10 Apr 2019, 2018). Major part of plastics become a waste on landfill and will take a rest for infinite time. Our ecosystem consumes microplastics and becomes sick. Disintegration of plastics actually gives off powerful greenhouse gases, contributing to climate change. Carbon dioxide and methane are well-known greenhouse gases contributing to global warming effect and also responsible for climate change up to some extent.

Keywords

Microplastic · Plastic wastes · Solid wastes · Climate change · Unsustainable approaches of solid waste

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13.1 Introduction

Solid waste is categorized into industrial waste, agricultural waste, municipal solid waste, medical waste, and hazardous waste. Waste can be defined as any substance which cannot be reduced, reused, and recycle. Globally nearly 70% of solid waste goes on landfill and 19% is recovered through composting or recycling. In India almost 70% of plastics fall in the category of discarded material, of total plastic consumption (CPCB 2013). Plastic consumption was five million tons in 2005, and eight million tons were reported in 2008, and also the growth rate of plastic consumption is expected to rise by 24 million tons up to the year 2020 (Singh and Ruj 2015). According to FICCI, the average per capita consumption of plastic in India is about 11 kg, and the Ministry of Petroleum and Natural Gas expected it would be 20 kg by 2022.

In many developing countries like India, solid waste management is struggling to achieve 100 percent efficiency in all hierarchical process like reduce, reuse, recycle, composting, incineration, and landfilling. With urbanization and changes in our daily life routine works, a lot of pressure increases on various processes of solid waste management (Srivastava et al. 2015). Further it increases emissions of global warming gases to environment.

Annual waste is expected to increase by 70% from 2016 to 3.40 billion tons in 2050 (World bank 2019). Significant amount of toxic heavy metals like copper, zinc, lead, and chromium is recovered from plastic waste in India (TERI 2018). According to TERI (2018), facts about plastic waste in India are as follows:

- Waste plastic contribution in total solid waste of India is 8%.
- Total plastic waste recycled is 60%.
- Carbon dioxide and methane gas emission from landfill only are nearly about 90 to 98% among other gas emission.

In 2005, the USA scored top rank in all over the world as a maximum CO_2 emitter (approx. 20 tons/capita/year), while India scored the 14th position (1.3 tons/capita/year) (Arceivala, 2010). While in 2010 China became the maximum CO_2 emitter country, the USA scored second rank. Developing countries are not bounded in Kyoto Protocol. Scored rank is based on CO_2 emitter rate based on the population. The Kyoto Protocol was first adopted in 1997. The United Nations make consensus how to reduce and control carbon emissions and promote carbon absorption.

13.1.1 Introductions of Plastics

Human created a wonderful material "plastic" for our easiness and usefulness. Bakelite is known as the first synthetic plastic created by Belgian-born American chemist Leo Hendrik Baekeland in 1907. It is a thermosetting phenol formaldehyde resin, which was commonly used for automotive component, industrial

Table 13.1 Classification of plastics and its application

S. no.	Plastic category	Applications in brief
1.	Polyethylene terephthalate (PET)	Drinking water bottles; soft drink bottles; food jars; jars for jelly, pickles, etc.; plastic films; textile fibers; processed meat packages; peanut butter jars; pillows; sleeping bag filling; etc.
2.	High-density polyethylene (HDPE)/low-density polyethylene (LDPE)	Food containers, woven sacks, bottles, plastics toys, milk pouches, metalized pouches, juice bottles, etc. Shopping and garbage bags, cups, and black plastic sheets
3.	Polyvinyl chloride (PVC)	Pipes, hoses, sheets, wire, cable insulations, multilayer tubes, electricity pipes, cooking oil bottles, food wrap materials, and building materials
4.	Polypropylene (PP)	Snack food wrap, straws, car batteries, disposable syringes, medicines bottles, car seats, batteries, and bumper
5.	Polystyrene (PS)	Pharmaceutical bottles, disposable cups, glasses, plates, spoons, trays, CD covers, cassette boxes, foams, laboratory ware, etc.
6.	Other thermoset, polycarbonate (PC), polyurethane (PU), FRP	CD, melamine plates, helmets, shoe soles

Source: Prasher (2018) and Banerjee et al. (2012)

applications, kitchen appliances, etc. Plastic is a revolutionary material, but unfortunately it has become an environmental threat globally to our ecosystem and for human health too (Frias and Nash 2019). By time, plastics have been categorized into various categories according to their chemical compositions and their use. Now plastics became a part of our urban lifestyle with a start of day to a good sleep, because of its amazing properties like flexibility, durability, high tensile strength, low cost, attain any shape, water resistivity, electrical resistivity, etc. Plastic has been categorized into various categories as given in Table 13.1.

Consumption of plastics in Indian cities grows rapidly day by day. Plastic products because of its large varieties hold space in each and every sector. Indian cities consume polypropylene plastics at maximum (25%), while polystyrene plastics (4%) are used at lowest end. It is important, to note here, that the second most consumable plastic is polyvinyl chloride (20%) (Banerjee et al. 2012).

Because of increased trend of e-commerce and increasing online shopping trends, packaging sector plays a very important role in the increase of plastic waste products. Banerjee et al. (2012) show packaging industry in India consumes 42% which is the highest consumption among all other sectors.

According to Sarah-Jeanne Royer (2019), low-density polythene on disintegration emits greenhouses gases like methane, carbon dioxides, etc., for example, tea coffee plastic disposable cups come under the category of low-density polythene which is recyclable, but in most part of rural areas and even in some part of urban areas of India, these disposable cups after single use become a part of municipal solid waste and lie on several years disintegrated and break into smaller pieces, hence providing large surface area and emitting greenhouse gases at the highest rates.

This is also the most prevalent discarded plastic in the ocean today. In 1960, plastics made up less than 1% of municipal solid waste by mass in the United States; by 2000, this proportion increased by an order of magnitude. By 2005, plastic made up at least 10% of solid waste by mass in 58% (Jambeck et al. 2015).

In most part of India whether it is rural or urban, incomplete incineration of plastic product is common. Improper incineration of plastics is more dangerous rather than without waste plastics open to environment. Improper or incomplete incineration releases toxic gases into the open environment.

13.2 Toxicity Associated with the Production of Plastics and Its Uses

Polyvinyl chloride releases hydrogen chloride gases when it is burned. Cellular phones contain a large number of hazardous substances like arsenic, lead, chromium, copper, nickel, etc., which can pollute the atmospheric air when it comes into the atmosphere after burning and can contaminate groundwater in the form of leachate through landfills (Nnorom and Osibanjo 2009). A large number of cellular mobile plastics become a part of waste of landfill, when directly dumped into the open atmosphere. A major part of housing units, in many areas, directly burn these cellular mobile phone plastics. Open burning practices of cellular plastics may be more dangerous.

Plastic leachate into freshwater can cause acute toxicity to *Daphnia magna* (Bejgarn et al. 2015). Bejgarn et al. (2015) also reveal that weathering the PVC material in artificial sunlight increases toxicity of leachates, whereas the PVC garden hose became less toxic. Uncontrolled burning of polyvinylchloride liberates hazardous halogens and pollutes the air, the impact of which is climate change (Verma et al. 2016).

The incomplete combustion of the following plastics can generate toxic substances as follows (Table 13.2):

Toxic emission from incomplete burning of plastics can be reduced by providing controllable complete incineration of plastics, and end product may be CO_2, carbonic acids, and water (except burning of PVC, as it produces HCl during burning). According to the World health Organization, melamine has been classified as group

Table 13.2 Toxicity of various plastics

S. no.	Plastics	Toxic substance produced after incomplete combustion	Effect
1	PVC	Dioxins, pyrene, chrysene, etc.	Contribution to climate change and health risk to human and animals, mercury vapor, ethylene dichloride
2	LDPE and HDPE	VOCs and semi-VOCs like olefins, paraffin. Aldehydes, light hydrocarbons	Benzene among VOCs is a well-known carcinogen
3	Plasticizers	CO, smoke	Di(2-ethylhexyl) phthalate (DEHP) is a probable human carcinogen
4	PE, PP, PS	CO, smoke	CO, smoke

3 carcinogenic substances. Melamine is continuously used in making thermosetting plastics, melamine foam, a polymeric cleanser (Kai-ching Anthony Hau et al. 2009).

13.3 Recycling of Plastics

Sustainable solid-based management approach is based on 3Rs (reduce, reuse, and recycle). "Reduce of plastic solid waste" is a serious issue, but at same time, it depends upon a number of factors like awareness among the people related to solid waste and their ill effect, education of people, lifestyle of people, developed or developing stages of place, implication of environmental laws, and act of solid waste management. "Reuse of plastic solid waste" depends on the properties of used or consumed plastic products. Most of the plastic products of daily routine work in Indian cities are not in the tendency of reuse; hence, they become gradually part of municipal solid waste. "Recycling of plastic waste" can be a good option, but in Indian scenario, it is not coming as an essential part of the solid waste management approach, maybe because recycling of plastic waste is a costly matter. Presently, plastic is an unwanted but essential part of municipal solid waste especially in dumping yard and sanitary landfills. Recycling of plastic is one strategy for plastic wastes, although it has some limitations. Plastic waste should be separated from landfill and goes for treatment before it becomes garbage of landfill. Indian technologies can concert 1 Kg of plastic to 750 ml of automotive grade gasoline. Plastic can be recycled 7–9 times only (TERI 2018). Table 13.3 shows the feasibility of recyclability of various types of plastics.

Table 13.3 Various type of plastics and its recyclability

S. no.	Name of plastic	Recyclability
1.	Polyethylene terephthalate (PET)	Easily recyclable
2.	High-density polyethylene (HDPE)/ low-density polyethylene (LDPE)	Most commonly recyclable plastic as it does not break under exposure to extreme heat and cold
		Recyclable but not all recycling facility has the option to recycle LDPE
3.	Polyvinylchloride (PVC)	Least recycled. Called "poison plastic" as it contains toxins
4.	Polypropylene (PP)	Can be recycled but difficult
5.	Polystyrene (PS)	No. It breaks easily making it harmful to the environment. Found on beaches all over the world
6.	OTHER thermoset Polycarbonate (PC) Polyurethane (PU) FRP	Not recycled

Source: Prasher (2018) and Banerjee et al. (2012)

Recycling is not always the best option, due to plastic's inherent properties (Banerjee et al. 2012). Recycling of plastic waste is not an easy one in Indian context, because segregation of various types of plastics is needed. One category of plastics can be a hurdle in recycling process to other types of category of plastics, if both categories of plastic are mixed in recycling processes. Recycling of plastics is a complex issue, as these are categorized into four categories: Primary is the mechanical reprocessing into a product with equivalent properties. Secondary is the mechanical processing into product's lower properties. Tertiary is the recovery of chemical constituent. Quaternary is the recovery of energy. At macroscale, recycling of plastics can create a problem, because various types of plastic resins are not compatible to each other at molecular level (Hopewell et al. 2009); hence, recycled plastic product may differ from parent plastic products. During recycling of plastics, product's certain amount of wastewater and heat are generated which can be further examined and properly disposed off. Incomplete burning of plastics can generate priority pollutants and greenhouse gases (Rochman et al. 2013).

13.4 Environmental Factors to Assess the Impact of Plastic Waste to Ecosystem

Plastics can withstand in the environment without degradation but also can emit various gases which can support global warming significantly. Plastic waste is an issue which is related to the human need, greed, comfort, and economy. For a sustainable management, a proper balance is needed between those parameters. Society plays an important role to manage plastic waste, because it is directly and indirectly affecting our ecosystem and our environment. According to Gironi F. and Piemonte V. (2011), the most important factors to assess the impact of plastic waste to our ecosystem are abiotic depletion, global warming, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicology, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication.

Life cycle assessment study done by Gironi F. and Piemonte V. (2011) reveals that CO_2 emission is maximum in case of PS which is equivalent to 5.98 kg CO_2 eq/kg just after nylon 6 which is equivalent to 7.64 kg Co_2 eq/kg. LDPE contributes 5.04 kg CO_2 eq/kg and HDPE contributes 4.84 kg CO_2 eq/kg. All carbon dioxide is not the same; thus not all carbon dioxide may be contributing to global warming (Chettri and Islam 2007). Wide varieties of plastic products are usable one time, and that's why they become a part of solid waste and nowadays liquid waste too. Carbon dioxide is about 2.8 times as dense as methane. Because of its high-density CO_2, it has tendency to move downward in case of landfills; further, it rises the temperature of landfill at lower level. If landfill is not engineered sanitary landfill, then it has chances to meet the groundwater, and on dilution in water, it lowers the PH of the water.

13.4.1 A New Threat to Ecosystem: Microplastics

Nowadays, one more category of plastic waste is identified, that is, microplastic wastes. Microplastics are developed by many big companies according to the increased use of microbeads in various applications like cosmetic products, daily useable products of our houses, and many more applications. On the basis of sizes, plastics can be categorized into three categories: macroplastics (sizes >25 mm), mesoplastics (sizes between 5 mm and 25 mm), and microplastics (sizes <5 mm). Further, microplastics can be divided in two categories, one having a size range between 1 and 5 mm and another having sizes between 20 μm and 1 mm. Classification of micro plastics still having diffrent arguments of diffrent agencies. According to (Adrian Strungaru et al. 2018):

EU Marine Strategy: 1–5 mm and 20 μm–1 mm
Technical subgroup on marine litter: 500 μm–5 mm and 1–500 μm
Hidalgo-Ruzand co-workers: first fraction >500 μm, for visual presorting and single spectroscopy measurement

Microplastic is defined as small plastic particles normally less than 5mm in size. According to Frias and Nash 2019, "Micro plastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1μm to 5 mm of either primary or secondary manufacturing origin from insoluble in water." Nanoplastics have colloidal behavior within a range of 1 nm to 1 μm. Microplastic particles found in a wide range of personal care product like shower gels, facial scrubbers, toothpaste, synthetic cloths, etc. are factory-made developed by many big companies. These microplastics are small enough to bypass the water filtration system; hence they wash down the drain with wastewater and become a new threat to our ecosystem. Factory-made microplastics and mechanically braked smaller pieces of plastics become a part of our natural system like in marine water, surface water, and groundwater; further, fish, invertebrates, and microorganism ingest micrometer-sized particles, which also come from synthetic clothing and cleaning products containing plastics (Rochman et al. 2013).

After various uses and being rejected from various waste treatment processes, finally plastic waste goes where? Plastic remains in wastewater and surface water. Source of water is a carrier to carry plastic pollution, for example, rivers collect all types of plastic waste (macro, micro and nano) and dumped it into sea and oceans. Moreover, the entire cycle of transporting these plastic wastes affects our ecosystem and human health and also contributes in climate change and global warming process. Our ecosystem consumes these microplastic wastes and becomes sick. Mammals, reptiles, and birds can also be harmed through eating plastics. A study shows 45% of marine mammal species and 21% of seabirds can be harmed because of plastics (Rochman et al. 2013). Macro- and light-weight plastics become a waste on landfill and will take a rest for infinite time. It enhances leachate's carcinogenic properties and contaminates groundwater. Surface water can be treated, but treatment of groundwater is not that easy, and sometimes in some circumstances, it is impossible to treat contaminated groundwater.

13.5 Strategies

- *Financial inputs*: In case of solid plastic wastes, there is a need to generate income to incorporate plastic waste pollution effect.
- *Public awareness*: For sustainable approaches, public should be aware of the use of plastics, properties of plastics, plastic's varieties, and lifecycle and toxic behavior of plastic products in various stages of uses and wastes. Awareness among the community people should be raised. Alarming situation has arrived now, and a collaborative approach should be welcomed.
- *Public participation*: A strong participation is needed in today's scenario to reduce, reuse, and recycle, as day by day for ease of life, we are more dependent on plastic products without knowing the other side of it becoming a garbage and ultimately affecting our whole ecosystem. The people should be educated to realize what plastics are taking from us, that is, comfort, easiness, and wide application ranges. The people should know the complete life cycle of plastic product from source to sink. The community should come from a comfort zone to sustainable comfort zone.
- *Legal structures and policies*: There is a demand of updated legal policies and laws based on local scenarios and researches.
- *Climate change and the environment*: To prevent the scenario of climate change by waste plastics and protect our environment, a collectively scientific approach in a whole life cycle of plastics is needed with strong and dedicated result-oriented determination.
- *Health of ecosystem*: Immediate attention is required toward the health of ecosystem, as plastic pollution in terms of macro- and microplastics, a threat that entered in our surface water and groundwater resources. Various technologies should be evolved and implicated, and redesign of water and wastewater plants unit should be on demand. Protection of groundwater contamination from plastic solid waste leachate from open dumping yard and landfills should be mandatory. Protection of surface water from microplastics should be made mandatory. Appropriate sustainable technological solution should be adopted by the municipalities and private parties.
- *Treatment of plastic waste should be based on chemical composition of plastics*: Plastic solid wastes have a small fraction of total solid waste but have a wide variety of plastics with different chemical compositions; hence a complete treatment of plastics should be separate. Monomers and other ingredients of PVC, polystyrene, polyurethane, and polycarbonate can be carcinogenic and can affect organism in similar way to the hormone estrogen (Rochman et al. 2013).
- *Encourage sustainable alternate materials*: The use of bioplastics and biodegradable materials should be encouraged. A lot of work is needed on research of sustainable alternate materials having such type of properties as plastics. Such type of work should be encouraged.

13.5.1 Ban on Plastic Products

Whenever talk goes on decay of environment and death of animals because of plastic polyethylenes and other microproducts of plastics, one point always rises and that is immediate action should be on ban on plastic products. Is it possible to ban on plastic products? Apart from today's daily life routine, in rural and urban areas, plastics became a major part of an infrastructure sector which is a very important sector to boost Indian economy. Secondly, a lot of manufacturers are producing plastic products in the country. However, only a few of these are registered, while the remaining is not registered although they supply cheap plastic products with poor quality. It is in fact true that the making of plastic product consumes lower energy, but recycling it requires energy. Bad scenario with plastics starts when it became a part of waste either solid waste or liquid waste.

13.5.2 Uses of Biodegradable Plastics

Biodegradable plastics made from plant resins with the use of organic catalyst can be the best alternative of petroleum-based plastic products. Worldwide production of bioplastics is just 0.375% as compared with petroleum-based plastic production (Gironi and Piemonte 2011). Use of bioplastics helps to reduce CO_2 emission and also gives a cheap alternative to petroleum-based plastic products. Bioplastics are biodegradable plastics mostly degraded by composting method. Recycling of bioplastics is not possible yet. Biodegradable plastics can degrade within a week, although lot of researches is going on the improvement of biodegradable plastic properties.

13.6 Summary

"Prevention is better than cure," this quote has relevance in terms of plastic waste pollution. Plastic waste should be separated from landfill and undergo treatment before it becomes garbage of landfill. In summary, reuse and recycling of plastics can be better strategies for reducing plastic wastes, although it has some limitations. People should be aware about toxic effect of incomplete burning of plastics open to atmosphere and also know about its contribution toward global warming and climate change. Participation of various sectors (commercial, societal, and individual) on all possible level is required to protect our environment from macro-, micro-, and nano-plastic pollution. Few commercial sectors are doing great work to reduce carbon emission but need the identification and registration of unregistered manufacturers and mandatory laws and regulations for reducing and control carbon emission. There is a need for continuous researches to develop sustainable approaches to fight various types of plastic wastes to protect our environment and ecosystem. Production of bioplastics should be on large scale, and the government and private parties should promote awareness programs for using it to control global warming gas emissions up to some extent.

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14

Assessment of Public Acceptance of the Establishment of a Recycling Plant in Salfit District, Palestine

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Abstract

The reduce-reuse-recycle (known as 3Rs) principle needs to be applied in developing countries in order to achieve waste minimization and local environmental goals. This book chapter presents the outcomes of a field study in Salfit district (Northern West Bank, Palestine), which aims at assessing the public acceptance in case of a recycling plant establishment. In Salfit district, almost 98% of the generated waste is collected among urban and rural areas, but until currently, it was disposed to open dumps.

The findings of a field survey in Salfit show that 98% of the population assent to the implementation of a recycling facility. Most importantly, almost 84% of respondents claim knowledge of waste source separation. Training may bridge and fill in the existing institutional and financial gaps. Overall, research results find the paths to better communicate with citizens during the application of new waste management systems. Public acceptance levels as investigated and presented in this paper had a direct effect and encouraged private sector to invest in solid waste management that was highly intended by local authorities and is expected to contribute largely to citizens' well-being and environmental protection.

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Keywords
Solid waste · Recycling · Developing countries · Public acceptance

14.1 Introduction

Municipal solid wastes (MSW) are defined by Environmental Protection Agency (EPA) as waste consisting of everyday items “used and then thrown away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries, which come from homes, schools, hospitals, and businesses” (USEPA 2018). This definition excludes hazardous waste, construction and demolition waste and agricultural waste that should be treated in specialized facilities. The handling and disposal of MSW is a growing concern as the volume of waste generated continues to increase. Typical management methods for municipal waste include landfilling, incineration, recycling and composting (Center for Sustainable Systems 2015; Srivastava et al. 2015).

There are many benefits associated to recycling which are linked to each other, but they all aim at minimization of the waste to be disposed, reducing landfilling cost and extending the existing landfills lifespan providing more land available for other uses. Simultaneously, trading of recyclable materials offsets the incurred collection and processing costs and elevating local socio-economic status (Eco. Cycle 2006). Natural resources are conserved since secondary raw materials may be applied effectively in manufacturing and industrial production processes. The latter contributes to innovation, entrepreneurship, green growth and new jobs through circular economy practices. Most importantly, recycling and remanufacturing (involving secondary materials) generates 194 times less greenhouse gas emissions compared to the manufacturing and processing of raw materials (Eco. Cycle 2006). Recycling, therefore, closes existing material loops, as proposed by the EU Circular Economy Action Plan that includes measures to stimulate Europe’s transition towards a CE; boosts global competitiveness; fosters sustainable economic growth; and generates new jobs, meeting with the EU2020 strategy set priorities.

Source separation and recycling are schemes that constitute a daily activity for many citizens worldwide and along with that an effective way to protect the environment and stimulate the economy (East-West Gateway Council of Governments 2005). Furthermore, source separation constitutes a significant step towards establishing a waste recycling scheme, mostly from environmental and economic point of view (Aziz et al. 2011). Qualitative and quantitative analyses based on field research outcomes constitute a prerequisite towards organizing recycling schemes (Chen and Christensen 2010), and facilities implementation supports and fulfils this scope.

Typically public perception must be taken into account early in the decision-making process, with the public informed and engaged from the start. There is a pressing need for people not simply to accept but to understand and appreciate the need for infrastructure, the nature of infrastructure investments and development, the costs and the benefits involved and the technological aspects (Kirkman and Voulvoulis 2017). Additionally in order to explore the most suitable MSW scenarios in any location, researchers should not only need to consider the influence of economic and environmental factors but the social acceptation as well (Nie et al. 2018). However, protests among local residents still exist, shedding doubt on the effectiveness of any similar initiative (Ren et al. 2016), but conflicts may be minimized once studies on uncertainty and causation are linked to overcoming severe environmental outcomes, impacts to human health as well as analysis of the willingness to pay (WTP). Socio-economic variables and local attitudes towards sacrifice cost or compensation ended up in proving that some variables, such as age, economic risk, treatment method and doubt regarding compensation, lead to protests (Ren et al. 2016). Also a wide variety of contextual factors at regional level exist which determine whether or not local residents of a region engage into the transition: culture (e.g. traditions, beliefs, historical experiences of previous energy transitions, trust in the transition), climatic conditions (e.g. availability and perception of natural resources), socio-economic and infrastructural factors (e.g. business opportunities, energy prices, interest in regional economic development), political and policy issues (e.g. the distribution of power at a region, stability of local current energy policies) (Fetanat et al. 2019).

The perceived risk is significantly influential on local public acceptance as the locals concern more about risk rather than benefits (evidence of NIMBY effect), primarily related to site selection (Li et al. 2019). Socio-political factors such as (dis)trust in stakeholders and perceived procedural unfairness have been found to affect public acceptance level directly and indirectly as moderating effect (Arning et al. 2019).

The acceptance issue/problem is a dynamic process rather than a static feature of new practices adoption because of the existing contextual factors and the influential variables that are not static. The locals are an important part of these factors, and their involvement in the adoption of new projects is one of the ways in which the factors influence the successfulness of them (Fetanat et al. 2019).

To this direction the government ought to establish dialogue with local public in terms of potential risks and help local public to form a rational attitude towards newly established facilities in MSW management field, enrolling locals in the entire process of location selection, improving trust levels and perceived fairness and reducing NIMBY effect (Li et al. 2019).

This paper discusses the results of an extended field research conducted to assess the public acceptance of the establishment of such a facility in Salfit district after offering the study participants a profound knowledge about the upcoming application of MSW management schemes and the implementation of waste management facilities both highly rely to public acceptance level and other relevant social aspects in order to address the targets set initially during the planning period (Ibanez-Fores et al. 2019).

14.2 Background and Research Initiative

Open dumpsites and indiscriminate dumping are common in all developing countries (Palestine included) particularly in the low-income and peri-urban areas. The SMW sector in the West Bank is struggling due to the unstable political situation in the Palestinian territories, and the economic status provides limited recycling incentives, with the exception for items of potentially high net value, such as end-of-life vehicles recycling scheme in Nablus (House of Water and Environment 2009). Additionally, given that the occupied Palestinian territories are relatively small in size and industrial activity is limited, the recyclables industrial processing is equally limited, and it is expected to remain so at least in the short to medium term (Hamadah 2011).

In Palestine, the institutional capacity is limited regarding MSW management in certain localities, as many of the small village council's financials are not adequate neither to involve permanent crew nor to provide sustainable collection services (Ministry of Local Government 2014). Local councils rely heavily on the amount of money coming from citizens' fee payment in the field of MSW management. Unfortunately, the collected amount is usually not sufficient to recover the cost of MSW management (Ministry of Local Government 2014). In many localities, high percentages of the population avoid paying fees for solid waste collection services according to local authorities' personnel, but lately this is avoided since the MSW management fee is included in electricity bill. Nevertheless, pre-existing debts have not been paid by some residents, creating financial fail out to the local MSW management services. Potential increase of the imposed fee level results in deterioration of the locals life status, on the one hand, and denial of some citizens to pay the fees, on the other hand, both leading into lose-lose situation.

As result of MSW mismanagement, major negative impacts on water resources, the environment and the health of Palestinian citizens (Khatib and Al-Khateeb 2009) are spotted.

Most of the municipalities and village councils (98%) provide sustainable solid waste collection service to their residents, but in some localities (mostly the rural areas), it is performed less than three times a week (Khatib and Al-Khateeb 2009). This situation leads overall management to still rely on dumping and/or burning in open areas. To improve current status in MSW management, the Palestinian authorities developed the National Strategy for Solid Waste Management (NSSWM) for 2010–2014. It proposed policies on the development of MSW management systems to enhance the quality and effectiveness of services, its availability to all citizens and safe and efficient disposal of solid waste in centralized sanitary landfills. In the context of the strategy, it is proposed to undertake actions to reduce the generated waste mass and the environmental impact. In 2017, the State of Palestine launched the second strategy for solid waste management, 2017–2022, in which much concentration is presented on the minimization, reuse and recycle of solid wastes, as there are limited areas suitable for the construction of sanitary landfills in Palestine. It emphasized that the private sector has to take the initiative and participate in the managing and development of waste management, including the reusing, recycling and generation of energy (State of Palestine 2017).

Recycling and reusing are the appropriate methodologies proposed, and the alternative ones indicated are incineration with energy recovery and landfilling (being the last option). Recycling is preferred in the Palestinian strategy due to many reasons: limited space, limited finance for collection, political conditions and environment protection (Saadeh et al. 2019).

To address all recycling challenges, purse a MSW management sustainable path and appreciate the recycling-related benefits, the Joint Service Council for Solid Waste Management in Salfit district in 2015 considered the establishment of a recycling facility in Salfit district.

The successful operation of Sairafi station in Nablus (another city in the West Bank) encourages and supports all new recycling initiatives. The Sairafi station receives about 140 tonnes/day of household, medical and industrial solid waste, and the gate fee is NIS 15 per tonne (MA'AN Development Center 2010). It also operates as a collection point to minimize transportation costs for end-of-life cars that are afterwards transferred into a large container to the adequate processing unit. Overall, the facility is of great importance to the local MSW management and recycling practices and has managed largely to minimize solid waste environmental impacts, create new jobs and have satisfying financial returns to local municipal and village councils (MA'AN Development Center 2010). Following Nablus example and the added value of Sairafi station in local MSW management, the Salfit district authorities have undertaken initiatives to plan and implement a recycling facility locally. The characteristics of the facility were discussed in a series of meetings among council's MSW management personnel and representatives of the candidate contracting party (private company). Initially, Salfit Joint Services Council launched a tender for the recycling facility establishment. The facility would significantly contribute to solving the problem of illegal dumping (a significant problem of Salfit district) providing at the same time good returns for the local council. Generated MSW will not be deposited or incinerated, but capitalized efficiently and economically since Maximum Yield Technology (MYT) would be applied to treat and recycle MSW. The treated waste fraction was planned to be utilized for energy generation in the long term.

The planning period traditionally involves public consultation process to collect information that would improve overall project's operation. Prior to that, the Salfit district council highly appreciated to assess citizen's opinion regarding the facility establishment and overall public acceptance of it. The outcomes of this research (presented in this paper) aim at significantly assisting the establishment of the facility in Salfit, which will launch its operation under a PPP agreement (as decided by local authority on 2018). Overall, the main features of the agreement are that Salfit JSC should purchase the land for the project, implement access road works and provide electricity for the operation. Salfit JSC is committed to transfer at least 36,000 tonnes of waste annually to the contractor's location from the local governmental units served and has to raise this amount in a period of 20 years to reach 120,000 tonnes per year (transfer from other LGUs). The facility gate fee is $~ 9.5/tonne (payable within 45 days from the invoice issuing) (Saadeh et al. 2019).

14.3 Methodology

Salfit district is located in the centre of Palestine, in the north-western part of the West Bank. It extends longitudinally from east to west, starting from the area of the extension Za'tara Street (Ramallah – Nablus road) to reach 1948 green line at the town of Kafr Kassem, naturally separated from Nablus and Tulkarem area from North Qana Valley and the South Sarida Valley, followed by Ramallah and Al-Bireh district (ARIJ 2008). Salfit area consists of 204 km^2, about 3.6% of the total area of the West Bank (ARIJ 2008). It includes 20 communities (ARIJ 2008). The number of population in the mid-2019 in Salfit district is estimated to be 78,380 inhabitants (PCBS 2019). Most of Salfit district area (75%) is classified as 'Area C', according to which is under the full control of Israeli occupation authorities (ARIJ 2008).

To assess local acceptance levels on waste management facilities establishment, a descriptive study was conducted in Salfit during 2014 and 2015, and the mean was the application of a structured questionnaire which was divided into three sections:

- Participants' socio-economic characteristics
- Assessment of current MSW management practices (know-how, attitude and applied practices)
- Provision of information on the upcoming facility profile and assessing participants' acceptance level as well as their level of willingness to participate in source separation practices that would foster the facility's operation

The questionnaire involves questions on future waste management schemes application and potential facilities establishment based on the currently enacted government policies on waste management field. It takes into consideration the financial situation locally, previous waste composition data. All aforementioned are investigated under the perspective of participants' level of education, household economic condition, etc. Local waste management administration, existing waste management plan, local recycling initiatives, existing technological and human resources and presumed land availability (Mwanza and Mbohwa 2017) are aspects that the participants were invited to assess.

The survey targeted households in both rural and urban areas of the district, and the questionnaire was randomly distributed to male and female heads of the households. Education level and income status were chosen as typical indicators of social status assessment in order to group participants' sample. To ensure validation of the field research results in Salfit governorate, local population (number and characteristics) data was crosschecked with Palestinian Central Bureau of Statistics (PCBS), to ensure study results can be used to derive conclusions that will apply to the entire population. Three communities in Salfit are considered urban communities by the Palestinian Central Bureau of Statistics, including Salfit, Biddya and Az-Zawiya. Five communities are classified rural communities, including Sarta, Qarawat Bani Hassan, Mas-ha, Deir Istiya and Yasuf. Figure 14.1 illustrates urban and rural communities of Salfit district (Adopted from the Department of Geography, Birzeit University).

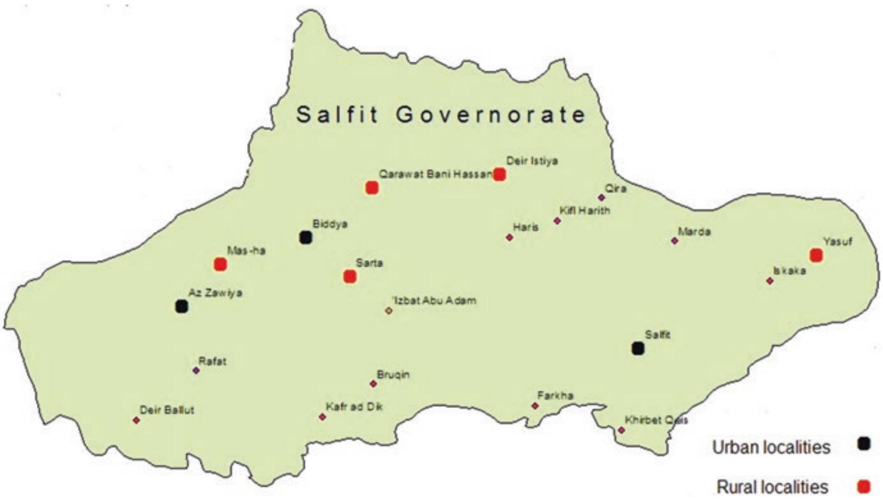

Fig. 14.1 Urban and rural communities of Salfit district. (Adopted from the Department of Geography, Birzeit University)

The research sample was selected to be a representative population having a good size to warrant statistical analysis. The survey assumed a normal distribution. The sample size was estimated according to Larkin and Simon (1987) equation:

$$n = \frac{p(1-p)}{\left(\frac{\mathrm{SE}}{t}\right) + \left[\frac{p(1-p)}{N}\right]} \tag{14.1}$$

where:

n: sample size
p: the estimated value for the proportion of a sample that will respond a given way to a survey question (50%)
N: population size
t: the value (1.96 for 95% confidence level)
SE: error proportion = 0.05

Based on Eq. (14.1) outcome, the sample size is 384 including 145 from urban areas and 239 from rural communities. Table 14.1 shows the percentage of study participants distributed in the two locality types.

The researchers formed a team of reviewers who were trained and performed mock interviews to ensure participants' full understanding of the questionnaire. Afterwards, the questionnaire was piloted on a small sample size to ensure adequate collection of data form participants. During the data collection phase, filled questionnaires were delivered to researchers daily, and random quality control was run

Table 14.1 Distribution of respondents for recycling plant surveyed according to locality type in Salfit district

Urban locality	Number of respondents	Percent (%)	Rural locality	Number of respondents	Percent (%)
Salfit	59	40.5	Sarta	44	18
Biddya	55	37.5	Qarawat Bani Hassan	69	26
Az-Zawiya	31	22	Mas-ha	38	23
			Deir Istiya	59	22
			Yasuf	29	11
Total	145	100	Total	239	100

for 20% of the respondents through telephone calls. Questionnaires that bared mistakes and mismatches or were half-filled were discarded and replaced with new ones properly filled in.

Data analysis was performed using the Statistical Package for Social Sciences (SPSS) version of a computer program 17. Descriptive statistics such as frequencies, means and ranges were computed.

14.4 Results and Discussion

According to the household survey, the sample distribution was 37% in urban localities and 63% in rural localities. The sample distribution on the basis of demographics and socio-economic characteristics in the study area was as follows: About 23% of the respondents were females and 77% were males, and the age group 21–35 constitutes the age group of most respondents (45.3%). More than 93% of the respondents live in independent houses, and the rest live in apartments. More than 54% of the respondents have a college degree or a postgraduate while only 8% have basic education.

This research focused on exploring ways of using citizen science to both monitor the environment al culture and investigate the acceptability level in future undertaken initiatives regarding this field.

The hierarchy of Salfit district issues of concern as perceived by locals is hereafter indicated; 44% pointed out 'lack of infrastructure' followed by 'lack of wastewater management' (22%) and 'district's insecurity and unsafety' (17%). MSW management issues (e.g. quality, effectiveness, applied technologies) concern approximately only 1 out of 10 locals, maybe because in all investigated communities (~98%) MSW is frequently collected. Figure 14.2 summarizes those findings.

14.4.1 Solid Waste Collection Services Assessment

As already mentioned, almost all (98%) communities have a solid waste collection service in the study area. A series of ten questions was applied to identify the current situation of the service and communities' satisfaction with the offered local solid

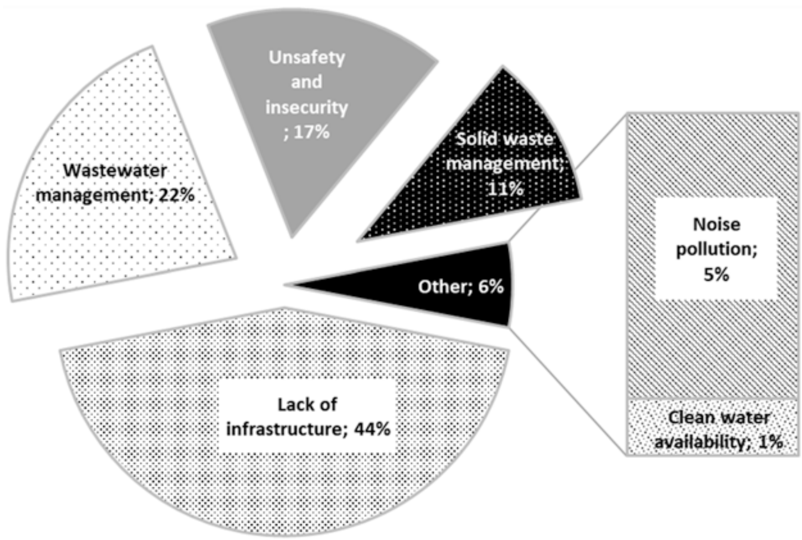

Fig. 14.2 Locals' main fields of concern in Salfit district

waste collection services. It was found that only 10% of the population perceives good quality of the offered was collection services of the Joint Services Council and described it as 'good' service. Almost 3 out of 10 (27%) expressed no opinion, confirming locals' disregard originating by the low level of environmental awareness and culture. The remaining 63% perceive the service as being of fair or poor quality as also showed in Fig. 14.3. It is considered quite discouraging for the local authority that despite the frequent collection services the locals value so low the offered MSW management services. Simultaneously this finding is a good indicator proving that local population expects more actions in the field of MSW management than just waste collection. The request for sustainability and application of modern solutions is largely depicted in this finding, highlighting the need for changing the local set priorities in MSW management field and targeting higher environmental goals that will benefit both the environment and locals' health.

The local plan includes a 3-day collection of MSW, but respondents indicated various frequencies based on their residency site; ~21% of population have a daily basis collection, 23% every 2 days, 46% every 3 days, and 8% once a week. Further analysis proved that mostly urban areas have one- or two-day-per-week-collection plan of MSW. Overall, approximately 56% of respondents declare medium satisfaction on the collection services provided in their area, 19% were satisfied and 24.5% were not satisfied.

Current fee of solid waste service varies between 10 and 15 NIS/month depending on locality. The price range is based on factors such as distance from landfill facility, the number of collection employees per locality, etc. Almost all (99%) survey participants regularly pay the fee as it is included in the electricity invoice. Overall 98.5% of the population has a waste container, whereas 39% consider their number insufficient

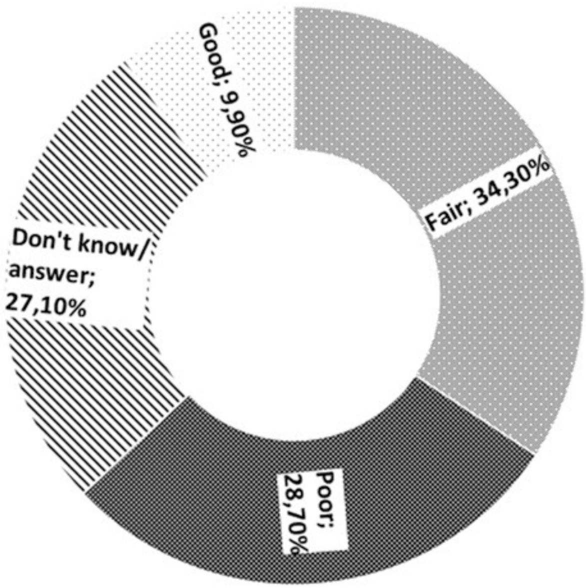

Fig. 14.3 Participants' perceived quality of the locally offered solid waste management services by the council in Salfit district

and 16.4% has to walk a long distance to dispose the generated waste. Half of the population pointed out that sometimes the containers are overfilled and 43.8% of respondents come across with aesthetic pollution as a consequence. Open fire in waste containers is frequently noticed by 18% of total respondents.

Figure 14.4 shows the optimum MSW Management hierarchy as perceived by survey respondents. Recycling constitutes the highest percentage (73%), serving the purpose of the research and the local authority intention for environmental sustainability.

Figure 14.5 summarizes the identified problems and faced obstacles to recycling in Salfit district, according to the respondents of interviewees. The limited awareness level among local population is featured as the most influential issue by far as it could endanger the overall facility operation (input recyclables being a lot less than the facility's capacity). Notwithstanding this is an obstacle that can be easily overtaken through the organization of communication campaigns, workshops and meetings implementation and organization of seminars addressing the youth as well as any interested party on recycling/sources separation issues. Following that and in relevance to local situation (as already described in Chap. 2), financial limitations (18.75%), limited infrastructure (13.28%) and Israeli occupation (12.50%) are reported by participants as the dominant obstacles. As in all developing countries so is in Palestine, technology transportation (even tested ones for years, e.g. recycling) bears a high probability of not offering the expected outcomes in the long term, as local authorities may not be able to financially support its operation or local personnel does not have the necessary know-how to maintain it. Both mentioned parameters come in agreement with Salfit

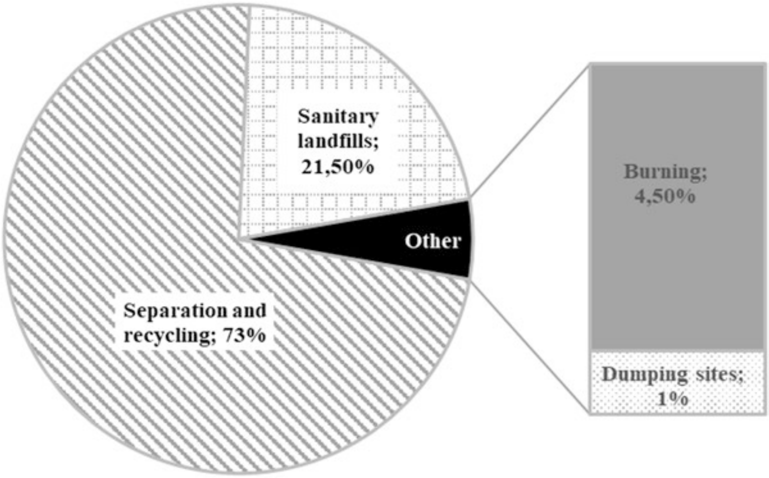

Fig. 14.4 Respondents' optimum solid waste management hierarchy as perceived by research respondents in Salfit district (reference year 2015)

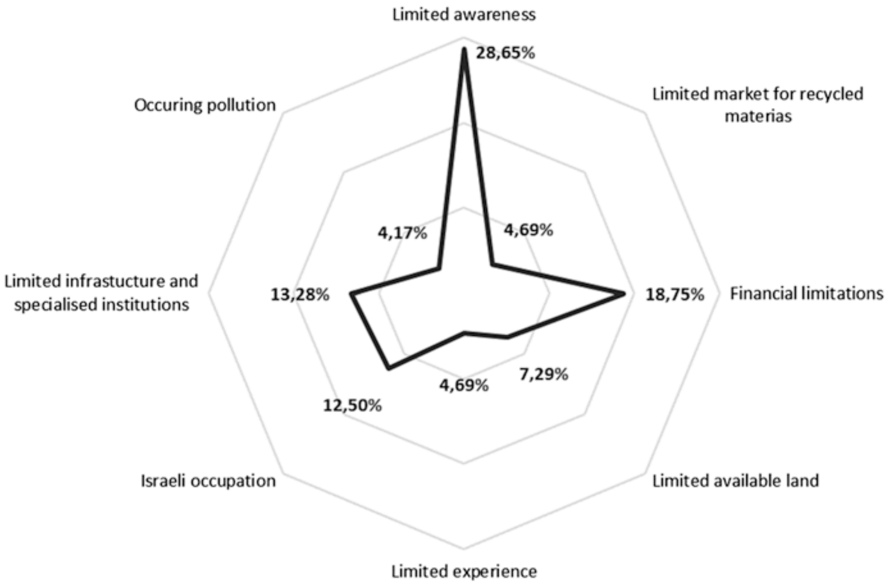

Fig. 14.5 Assessment of the local problems and obstacles on the application of solid waste recycle schemes in Salfit district (reference year: 2015)

local authority responsible personnel and have been already taken into consideration by them since they favour the facility establishment under a PPP agreement. Other stated obstacles are not considered by researchers as important ones, since the successful operation of the nearby recycling facility of Nablus proved that the selection of a local sustainable roadmap may alter local situation and create green growth, environmental benefits and new jobs. Setting a good example by the establishment of such a facility will definitely influence local educational institutes to develop undergraduate, MSc and PhD programmes to develop scientists with updated environmental knowledge and technological expertise who may be involved in facility's operation targeting its successful operation and at the same time providing local personnel with relevant experience on the field.

Regardless of the highlighted obstacles, 98% of respondents agree for the establishment of a recycling plant in Salfit district, and it is rather encouraging that 65% of research respondents are willing to volunteer in campaigns aiming at establishing 'clean communities'. The latter constitutes a great starting point for the launching of communication campaigns aiming at raising awareness on environmental issues and increase citizens' participation in relevant practices applied locally, as the success of any recycling program globally depends mostly on the active and sustained participation of citizens (Kattoua et al. 2019).

14.4.2 Public Awareness and Willingness for Source Separation and Recycling

Environmental education is a prerequisite of an effective application of recycling schemes. The required effort that has to be put to disseminate the scope and raise awareness in recycling themes (including source separation) needs to be assessed prior to planning phase. The results of the research in Salfit district present populations' high awareness level regarding the importance of recycling and the high environmental/economic benefits of future recycling schemes (see also Fig. 14.6). Despite the fact that 83% of respondents emphasized that they have not been officially informed on recycling practices, 95% of research respondents are aware recycling purpose and 80% of research respondents comprehend the existing high capacity to form new products with the usage of secondary raw materials.

It was found that 75% of respondents practice recycling permanently or sometimes. Unofficial recycling takes place locally since 65% of research respondents occasionally sell separated metal waste items to local businesses, collectors or scavengers. Part of the collected waste is recycled locally and another part is being sold and transported to Israel.

A critical negative impact of the council's miscommunication is the fact that 18% of the population pointed out certain – nonfactual – risks incurring from recycling process such as:

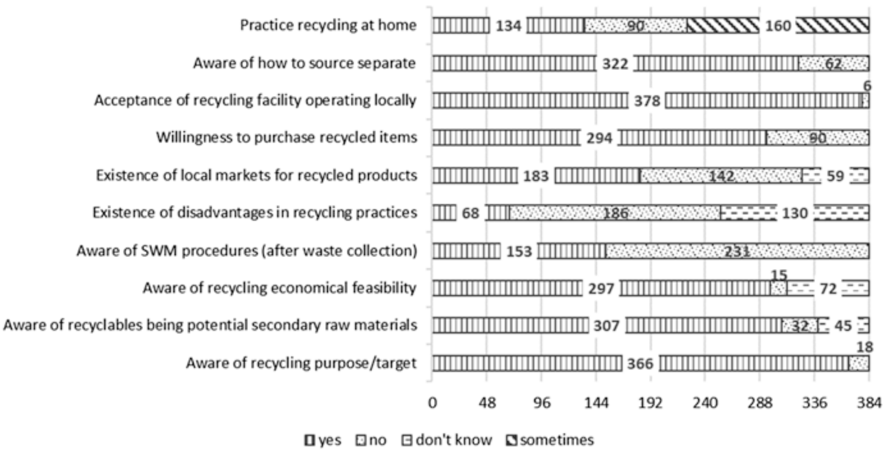

Fig. 14.6 Assessment of the awareness level and environmental culture of the Salfit residents on recycling practices (reference year: 2015)

- Pollution from the recycling process, focusing on air pollution resulting from the process of plastics melting process in industry
- Potentially low quality and import of health hazards of new products deriving from use of secondary raw materials (recyclables)
- High financial cost of recycling being a burden on citizens

Findings prove that beside the implementation of environmental campaigns, there is an urgent need to provide adequate recycling facilities and develop local recycling chain to increase environmental culture and encourage locals to participate in recycling practices, proved to be feasible for effective waste minimization and environmental protection, also pointed out by Wan et al. (2017).

About 84% of respondents have the necessary know-how to practice source separation at home, and 48% of respondents believe that the local market is ready for the incorporation of secondary raw materials. Overall, and regardless of their educational level, the survey respondents pointed out their willingness to participate in source separation practices at home to assist the local recycling scheme and operation of the facility.

When it comes to disposing organic household waste, 75% of respondents mentioned that they dispose it with other domestic wastes as shown in Fig. 14.7; the latter excludes dry plants/wood that 77% of research respondents use for heating purposes as this practice minimizes the households budget compared to usage of gas and oil products. About 10% of the investigated households have undertaken initiatives and produce compost out of organic household waste, given that Salfit district is considered an agricultural area.

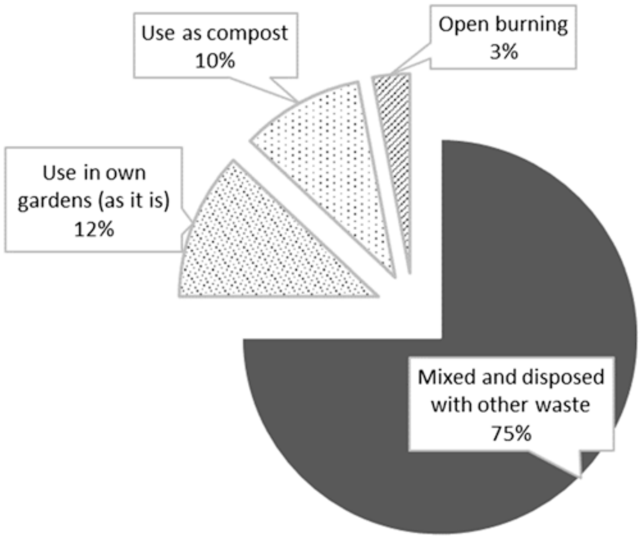

Fig. 14.7 Disposal methods followed by local population to manage generated organic household waste in Salfit district (reference year: 2015)

14.5 Conclusions and Recommendations

Respondent's knowledge of solid waste management and its effect on health and the environment was good. Poor infrastructure and lack of wastewater management are the highest-rated sources of concern for residents of Salfit district. Waste collection services extent in Salfit covers 98% of the citizens with average collection frequency once every 3 days. The highest percentage (84%) of residents is ready to sort and separate the solid waste in their homes. This is an indicator for the necessity of supporting the adequate investment for establishing a recycling centre for valuable materials (i.e. implementation of advanced and satisfactory domestic solid waste management system). Most of the respondents (98%) are supporting the establishment of a waste recycling facility in the district.

Training and education plans for the general public should be conducted in order to decrease the amount of waste produced, encourage the public to practice source separation of waste and pay their old debts to local councils since current fee collection is through electricity bill. The government regulations and laws should be developed to implement appropriate solid waste management system. Hence, enforcement of legislation should be emphasized, as it is more significant than the survival of the rules. Finally yet importantly, there is an urgent need to provide adequate recycling facilities and develop local recycling chain to increase environmental culture and encourage locals to participate. To this direction, the private sector should be encouraged to invest in the solid waste sector in the form of PPPs, which is an option local government favours and considers as the best solution to address local MSW management issues as well as the limited resources in terms of infrastructure, experience and financial capacity.

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An Overview of the Technological Applicability of Plasma Gasification Process

15

Spyridon Achinas

Abstract

Recent increased environmental and political pressures, the unstable perspective of the fuel prices, and the fossil-resource-based energy have risen the industrial interest into the energy that can be produced from waste and have enhanced the technological findings in waste-to-energy sector. Sustainable waste treatment is an essential element in efforts to improve sustainability. Plasma gasification is considered an alternative for the abatement of municipal waste and has been demonstrated for the treatment of various wastes more in Japan, Canada, and the USA than in Europe. The goal of this mini-review is to brief the plasma-based gasification technology. This study includes a technological overview of the PG process, a survey of existing PG facilities, a comparison with other thermal techniques, and an identification of its environmental impacts.

Keywords

Plasma gasification · Waste management · Sustainability · Green energy · Thermal technology

Highlights

- We summed up the plasma gasification technology.
- Survey of waste treatment facilities worldwide using plasma gasification.
- Technical and environmental comparison with other thermal technologies.
- Barriers on the plasma gasification application are addressed.

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15.1 Introduction

Recent increased environmental and political pressures, the unstable perspective of the fuel prices, and the fossil-resource-based energy have raised the industrial interest into the energy that can be produced from waste and have enhanced the technological findings in waste-to-energy sector (Tendler et al. 2005; Vaish et al. 2016, 2019). The disposal of waste remains a crucial issue, as stockpiling or landfilling of garbage has a negative impact. The European countries have to improve their waste management policy according to the Waste Directive Framework (Directive 2008/98/EC) for sustainable development, but the lack of project investments is apparent, and the problem persists.

Plasma gasification (PG) is a thermochemical process whereby wastes (produced or currently being landfilled) are converted into valuable energy in the form of gaseous fuel (syngas) that can be used for heat, power, or biofuel production. PG technology aims to the destruction of waste using high temperature (Fauchais 2007). Several companies through their representative solutions have facilities in various stages of permitting, constructing, or planning worldwide that could potentially destruct different wastes. However, PG facilities globally are currently operating under stringent regulations with different wastes, and it is expected that the facilities equipped with the most advanced air pollution control systems will be able to meet or exceed the regulatory restrictions in Europe.

The goal of this review is to provide a technical overview of the potency of the PG application. This assessment includes a technological analysis of the PG process, a survey of existing PG facilities, an assessment of the environmental aspects of PG technology, a characterization of useful end products, and a generic approach of PG economics incorporating operating costs and revenue potential from PG operations.

15.2 Plasma Gasification Technology

15.2.1 Feedstock

In a typical plasma gasifier, the feedstock enters from the top to the bottom of the furnace. It was found that PG technology has considerably expanded in the areas of municipal solid waste (MSW), fly ash, and hazardous and industrial waste (Leal-Quirós 2004; Serbin and Matveev 2010). Although the demonstration of PG to hazardous feedstocks is limited worldwide, no significant technical barriers to the application of this technology in processing hazardous seem to exist. This is particularly evident in the significant expansion of PG use, including feedstocks that are more heterogeneous than MSW, automotive shredder residue (ASR), tires, and mixed waste (An’Shakov et al. 2007; Dave and Joshi 2010).

15.2.2 Thermochemical Reactions

Gasification process includes various chemical reactions that are strongly dependent on the reactor conditions (temperature, gasification agent, etc.). While gasification processes vary considerably, typical gasifiers operate at temperatures between 700 and 800 °C (Basu 2010). The intrinsic gasification reactions are given in Eqs. 15.1, 15.2, 15.3, 15.4, 15.5, 15.6, 15.7, and 15.8 (Higman and Van Der Burgt 2008):

$$C + CO_2 = 2CO \qquad \Delta Ho = +172\,kJ \tag{15.1}$$

$$C + H_2O(g) = CO + H_2 \qquad \Delta Ho = +130\,kJ \tag{15.2}$$

$$C + 2H_2O(g) = CO2 + 2H_2 \quad \Delta Ho = +88\,kJ \tag{15.3}$$

$$C + 2H_2 = CH_4 \qquad \Delta Ho = -71\,kJ \tag{15.4}$$

$$CO + H_2O(g) = CO_2 + H_2 \qquad \Delta Ho = -42\,kJ \tag{15.5}$$

$$CO + 3H_2 = CH_4 + H_2O(g) \quad \Delta Ho = -205\,kJ \tag{15.6}$$

$$C + 1/2\,O_2 = CO \qquad \Delta Ho = -109\,kJ \tag{15.7}$$

$$C + O_2 = CO_2 \quad \Delta Ho = -309\,kJ \tag{15.8}$$

It is notable that synthesis gases for liquid fuels and chemicals are composed of gaseous mixtures of CO_2 and hydrogen. The carbon monoxide–hydrogen ratio is varied under process conditions and is typically related to the range of products. In contrast, pyrolysis does not include a reactive step, and its gaseous yield is lower and cannot be used for direct fuel or chemical synthesis without further processing (De Souza-Santos 2008).

PG operates at elevated temperatures to break the feedstock to molecules (Higman and Van Der Burgt 2008). Plasma is generated by heating a gas to very high temperatures where the molecules and atoms are ionized and toxic compounds such as dioxins are completely decomposed to harmless chemical elements.

15.2.3 Plasma Gasification Unit

A PG facility includes a preprocessing unit (i.e., shredder), a feeding system, an equipment to process the by-product (slag) derived from the plasma furnace, a syngas treatment system, and a monitoring and control system. The main device of a PG facility is the plasma-based furnace and specifically the plasma torches (Bratsev et al. 2006a, b).

15.2.3.1 Plasma Gasification Vessel

The gasification vessel is the main design component in the PG plant. The choice of reactor type and torch configuration relies on the process conditions and the feedstock type (Bratsev et al. 2006a, b; Hrabovsky et al. 2006). Plasma gasification reactor (PGR) is a vertical furnace that is similar to that used in the foundry facilities for the melting of metallic materials. PGR can afford high internal temperatures and corrosive environment. The gasification reactions will convert the organic substance of the MSW feedstock into a syngas which exits the PGR, while the inorganic fraction will be transformed into a molten slag that exits the bottom. The PGR operates at elevated temperature in the lower part of the chamber, and oxygen and/or steam are injected into the process.

Two configurations of plasma gasifier (Fig. 15.1) are commonly used in industrial scale and are related to the placement location of the plasma torches. The typical configuration of a PG furnace is that the processed waste feedstock is fed into the furnace from the top. The electrodes which are responsible for the arc generation with the help of current extend into the lower part of the furnace, the so-called melting chamber. Gas enters the furnace through the torches and is ionized due to the high-temperature (up to 6000 °C) plasma jets applied. Various gases (O_2, air, N_2, CO_2, $H_20_{(g)}$) can be used with air to be the most cost-effective. Additional gas (most common air or stream) is introduced through the nozzles to control the gasification reactions. An alternative plasma gasification technique used in industrial scale combines the plasma technology and the common gasification. This technique is not considered exactly as a thermal PG technology but as a thermal plasma treatment of gases leaving the reactor. In this case, the plasma arc destructs the tars, toxins, and furans included in the syngas at the exit of the plasma gasifier (Fourcault et al. 2010).

The combined process is able to produce a clean synthetic gas (main components H_2 and CO) that can be used to generate electricity in combined heat power (CHP) gas engines or can substitute natural gas. The multistage process unit combines gasification and plasma conditioning. A main component of the process is the thermal aftertreatment of the syngas by means of generated plasma. It is necessary for

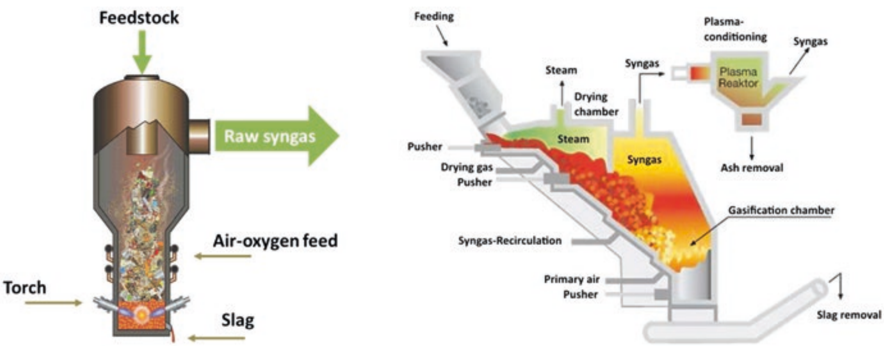

Fig. 15.1 Plasma-assisted gasifier from Alter NRG (left) and combined plasma gasifier from Europlasma (right) (Alter NRG; CHO-Power)

cracking and transformation of macromolecular hydrocarbons. Plasma torches are only used for the thermal cracking of the syngas and for slag vitrification.

15.2.3.2 Post-Processing Unit

The gaseous product exits the furnace that can be used for energy and fuel production. The thermal energy resulting from the syngas can be exploited in a variety of ways. These include the steam generation for further electricity and heat production. The design of the posttreatment equipment used to clean the effluent gases is crucial for the viable operation of a PG plant. Advanced emission control systems are required to meet regulatory standards. Typical process equipment for the treatment of exhaust gases consists of particulate filters, wet scrubbers, or electrostatic precipitators. Syngas is cleaned in a multistage process, the number of stages being dependent on how clean the syngas needs to be for the particular utilization and conversion process specified in each specific project. These multistage elements can add considerably to the capital costs and incur significant operating costs for the disposal of secondary residues. They can also reduce the overall plant operational availability and, in some circumstances, lower revenues from energy sales.

15.3 Survey of PG Facilities Worldwide

A literature-based identification of existing PG facilities was conducted, and their basic characteristics are given in Table 15.1. Alter NRG is a company with extensive experience and has built several commercial installations in Japan, China, the United Kingdom, and India. PEAT International, SRL Plasma, and InEnTec have also constructed facilities with a capacity up to 10 tpd using industrial, medical, and hazardous wastes. The pending PG projects were not identified in the analysis.

15.4 Products of PG Facility

The most crucial product from alternative conversion processes is the gaseous product so-called synthetics gas or syngas (Fig. 15.2). The syngas is a valuable gas with the main components CO and hydrogen. This synthetic gas can be used for fuel production, heat, or energy (Ducharme and Themelis 2010). The commercial applications of synthesis gas are split between chemical production, fuel production, and energy (heat/power) production. The percentage of PG facilities producing electrical power and utilizing post-combustion products has risen significantly due to demand and deregulation of electricity markets as well as accumulation of wastes.

Other potential products of PG processes include chemicals and fuels which can be stored and sold when the market price is higher. Inorganic materials in the feedstock are melted into slag, which is nonhazardous and can be used in a variety of applications, such as road construction and roofing materials. Marketing feasibility depends on the cleanliness, quantity, and packaging of the slag. Metal sources are also generated from the plasma gasification process. The metals produced can be

Table 15.1 Plants for waste treatment by plasma technique currently in operation around the world and plant projects for the next years

Technology supplier	Country	City, province	Owner	Capacity (tpd)	Feedstock	Output	Commission
Alter NRG	Japan	Utashinai, Hokkaido	Hitachi Metals	220	MSW, ASR	Power	2003
Alter NRG	Japan	Mihama-Mikata	Hitachi Metals, Hitachi	24	MSW, WW sludge	Heat	2002
Alter NRG[a]	Japan	Yoshi	Hitachi Metals, Hitachi	151	MSW		1999
Alter NRG	India	Nagpur	SMS Envocare	68	Hazardous waste	Power	2008
Alter NRG	India	Pune	SMS Envocare	68	Hazardous waste	Power	2009
Alter NRG	China	Wuhan, Hubei	Wuhan Kaidi	150	Biomass	Biofuel	2012
Alter NRG	China	Shanghai	GTS Energy	30	Medical waste, incinerator fly ash	Slag	2014
Alter NRG[a]	USA	Madison, Pennsylvania	Alter NRG	48	Over 100 tested	Syngas	1990
Advanced Plasma Power	United Kingdom	Wiltshire	NG, Stonehouse, PR, CNG Services	300	Waste, biomass	Syngas, power	2008
Advanced Plasma Power[a]	United Kingdom	Swindon, Wiltshire	NG, Advanced Plasma Power, PE	22	RDF	bioSNG	2017
Advanced Plasma Power	United Kingdom	Energy Park Peterborough			Mixed waste	Power	2014
CHO-Power	France	Morcenx		200	Cardboard, wood, paper, tissues	Power, heat	2012
Bellwether RG	Romania	Brasov	Dunarea SA	240	Calorific waste	Power, heat	2008
InEnTec	Japan	Iizuka	Fuji Kaihatsu Ltd.	10	Industrial wastes	Power	2002
InEnTec[a]	Japan	Okinawa	Kawasaki		PCB oil and PCB-contaminated materials		2003

InEnTec[a]	USA	Kapolei	Asia Pacific Environmental Technologies		Medical waste	Power	2001
InEnTec[a]	Taiwan	Kuan Yin (Taipei)	Global Plasma Technology Limited	4	Medical waste, batteries, solvents, lab packs, mercury vapor lamps		
InEnTec	USA	Arlington	InEnTec Columbia Ridge LLC		MSW	Syngas, H_2	
InEnTec[c]	USA	Richland	InEnTec LLC	4	Hazardous waste		1996
InEnTec	USA	Richland	InEnTec LLC		Hazardous and nuclear waste; TSCA and PCB waste		1999
InEnTec	USA	Richland	Allied Technology Group, Inc.		Mixed hazardous and radioactive wastes		1999
InEnTec	Malaysia	Kuala Lumpur	Boeing Company/ BioPure Systems				
InEnTec	Japan	Harima	Kawasaki Plant Systems		Asbestos		
InEnTec	USA	Midland, Michigan	Dow Corning Corp.		Industrial by-products		
PyroGenesis[b]	Canada	Montreal	PyroGenesis	0.5–2.5	Mixed waste		2002
PyroGenesis	USA	US Navy	US Navy	7	Shipboard wastes		2004
PyroGenesis	USA	Hurlburt Field	Air Force Special Operations Command	10.5	MSW, hazardous wastes		2011
Plasco Energy Group[a]	Canada	Ottawa		85	MSW	Power	2007
SRL Plasma – PLASCON[a]	Australia		Nufarm Limited	0.8	Chlorophenols, phenoxies, toluene, dioxins/furans		1995

(continued)

Table 15.1 (continued)

Technology supplier	Country	City, province	Owner	Capacity (tpd)	Feedstock	Output	Commission
SRL Plasma – PLASCON[a]	Australia		BCD Technologies	1	Concentrated polychlorinated biphenyl (PCB) waste		1997
PEAT International[b]	China	Shanghai	Abada Plasma Technology Holdings	1.2	Medical waste, oil refinery sludge		2013
PEAT International[a]	Taiwan	Tainan		4	Waste and toxic waste such as incinerator fly ash, medical waste, inorganic sludges		2005
PEAT International[a]	USA	Lorton, Virginia		7	Defense department waste, medical waste		

Alter NRG, CHO-Power, PEAT, InEnTec, PyroGenesis Canada, Tetronics International, Advanced Plasma Power, Plasma Arc Technologies, Plasco Energy Group, Westinghouse Plasma, Europlama

[a]Demonstration

[b]Pilot

[c]Test facility

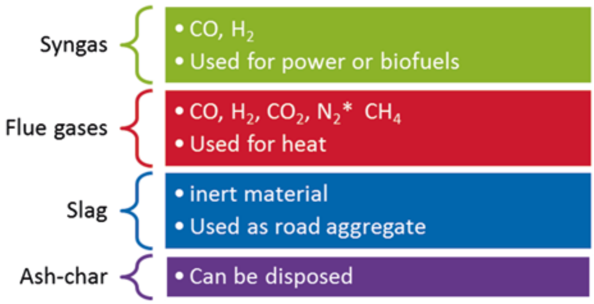

Fig. 15.2 Product range from plasma gasification operation

collected in molten form from subsequent processing in smelters. If the volume of metals is large enough to warrant separation, then the plant is configured to recapture metals. It is reported that slag derived from the vitrification of inorganic waste fraction has shown acceptable leachability limit and can be regarded as inert waste and therefore can be used as building components or disposed to a landfill.

15.5 Air Emissions from Plasma Gasification Operations

PG process is regarded as a promising technique to break down hazardous waste (i.e., medical waste) (Nema and Ganeshprasad 2002). It also displays lower environmental impacts in terms of air emissions and slag leachate toxicity as compared to other waste-to-energy processes, such as incineration (Hlína et al. 2006; Chang et al. 1996). However, empirical data on the environmental impacts of PG facilities are limited and depend on the local air permits and exhaust aftertreatment systems utilized at each facility. PG process has some emission advantages compared to conventional thermal treatment processes since it produces emissions far below the most stringent regulatory requirements. PG decomposes various types of wastes including low-strength radioactive waste to their elemental form. PG offers considerable environmental benefits with negative carbon footprint in comparison with other thermal energy technologies and has the highest landfill diversion rate of any available technology, making it very attractive to local authorities (Murphy et al. 2002). When compared to operations that utilize combustion of waste tires, it is generally accepted that PG technology will yield lower environmental risks and impacts in most areas. However, the information available is limited, due to the secrecy of full-scale PG facilities. Additionally, some older information on PG facilities may not be relevant due to recent advances in emission controls.

Air emissions may be the greatest environmental concern in PG operations. The output gases of plasma gasifiers contain a variety of air pollutants that must be eliminated prior to their release into the atmosphere. There are many strategies available for controlling emissions from PG process. The PG process differs in a number of key ways from common thermal processes, as the former generate intermediate gaseous products that can be converted into fuels or chemicals with almost no direct emissions. Information regarding output products of plasma gasification and problems that may be encountered is difficult to obtain as performance data from plasma gasification operations are often proprietary.

15.6 Market Potential of PG Technology

The profitability of any individual facility appears to depend on a number of other factors, including economic considerations, facility costs, feedstock availability, products range, and the permitting process (Artemov et al. 2012). There are several factors that affect the cost and ultimately the profitability of PG waste-to-energy conversion operations, and these are shown in Fig. 15.3.

The sensitivity of the estimated cost and expected revenues from the sale of syngas and heat coproduced by the conversion of waste depends on the world markets and prices for energy and industrial materials. At present, little data is available for currently operating facilities and how these facilities would be affected by market changes. The value of PG process is attributed to the combination of the avoided cost of conventional disposal and the expected revenue stream from coproduction (Popov et al. 2011). Table 15.2 summarizes information for different thermal technologies. Information was collected from (1) refereed technical literature and (2) commercial literature and/or referenced websites (Table 15.3).

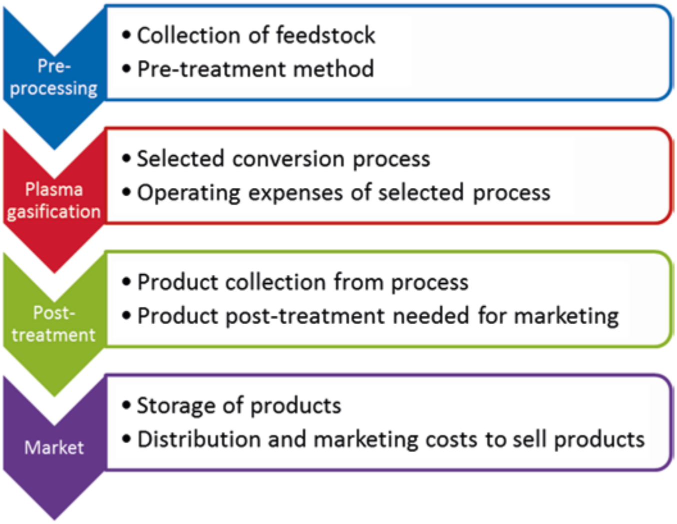

Fig. 15.3 Factors that influence the economic assessment of a plasma gasification facility

Table 15.2 Emissions from thermal plasma treatment facilities (Bowyer and Fernholz)

Emission	Unit	USERPA standard	EC 2000/76 standard	Unit[a]	Unit[b]	Unit[c]
PM	mg/Nm3	20	14	3.3	<3.3	12.8
HCL	mg/Nm3	40.6	14	6.6	2.7	3.1
NOx	mg/Nm3	308	281	74	162	150
SOx	mg/Nm3	85.7	70	–	–	26
Hg	mg/Nm3	50	14	0.0002	0.00067	0.0002
Dioxins/furans	ng/Nm3	13	0.14	0.000013	0.0067	0.009245

[a]EPA Environmental Technology Verification Testing (2000) of InEnTec Plasma Arc Gasification of 10 tpd of Circuit Boards, Richland, Washington
[b]EPA Environmental Technology Verification Testing (2000) of InEnTec Plasma Arc Gasification of 10 tpd of Medical Waste, Richland, Washington
[c]Results of Third-Party Demonstration Source Tests (2008–2009) of Plasco Energy Plasma Arc Gasification of 110 tpd of MSW, Ottawa, Canada

Table 15.3 Characteristics of different thermal technologies

Property	Pyrolysis	Incineration	Conventional gasification	Plasma gasification
Process temperature	500–800 °C	850–1200 °C	400–900 °C	1500–4000 °C
Atmosphere (agent)	Inert/nitrogen	Air	O_2, H_2O	O_2, H_2O Plasma gas: O_2, N_2, Ar
Feedstock	Biomass and MSW Low flexibility	Mixed MSW High flexibility	MSW, RDF, sludge, medical waste Medium flexibility	MSW, RDF, medical and hazardous waste High flexibility
Produced gases	CO, H_2, CH_4, other hydrocarbons, N_2	CO_2, H_2O, O_2, N_2, NOx, SOx, HCl, VOCs	CO, H_2, CO_2,H_2O, CH_4, N_2*	CO, H_2, CO_2, N_2*, CH_4
Solid phase	Ash, coke (biochar)	Ash (approx. 30% of initial volume)	Ash, char	Ash, char, inert slag (12% of initial volume)
Liquid phase	Pyrolysis oil and water	None	None	None
Emissions	N.A.	Far greater than (plasma) gasification	Less than incineration	Less than gasification and incineration

(continued)

Table 15.3 (continued)

Property	Pyrolysis	Incineration	Conventional gasification	Plasma gasification
Gas cleaning	Intermediate cleaning before gas utilization	Intermediate cleaning before gas utilization	Intermediate cleaning before gas utilization	Cleaner gas is produced after the plasma arc
Pollutants	N.A.	PM, NO_X, SO_X, fly ash, ash,	PM, tars, NO_X, SO_X, dioxins, furans, hydrocarbons, CO, char	Low levels of CO, NO_X, tars, other pollutants vitrified in slag
Energy recovery	N.A.	Lower resulting from excess air leading to more waste heat	Higher from less heat loss (not all chars are broken down)	Higher gross energy recovery
Energy use	N.A.	Heat to electricity (steam boiler)	Heat to electricity Syngas for electricity Other commercial uses	Heat to electricity Syngas for electricity Other commercial uses
Input energy requirements	N.A.	None	Autothermal, partial oxidation	Very high (1200–1500 MJ/tonne of waste)
Power to grid (kWh/ton MSW)	N.A.	544	685	816

Basu (2006, 2010), Higman and Van Der Burgt (2008), De Souza-Santos (2008), Annamalai and Puri (2006), Rezaiyan and Cheremisinoff (2005), Luche et al. (2012), Hrabovsky (2009), Kalinenko et al. (1993), Ghofur et al. (2018), Arazo et al. (2017), Huang et al. (2016), Moustakas et al. (2005, 2008), Mountouris et al. (2006, 2008), Achinas and Kapetanios (2012, 2013) and Bratsev et al. (2009)
NA not available

15.7 Barriers

Three cardinal issues must be addressed for any of PG technology to be implemented successfully: legislative/regulatory, involvement of market and agreements, and social aspect. Regulatory facet is the most essential obstacle for this alteration facility. The local authority must also play the dominant role in the management of solid waste, water, and air. The planned facility that comprises premises, classification, water supply, usableness, site design reconsideration, and air emissions must be audited by the local planning agency. It is obligatory for a PG facility to obtain permission hence to start its construction activities.

Safe agreements to obtain a feedstock availability are required for the profitability of PG projects. The amount of feedstock must be more or less stable through the project's life. A thorough estimation of advantageous and disadvantageous consequences concerning ecosystem, society, and profit must be acquired before a facility passes to the stage of building. If markets are not developed for recycled products from the presorting process, revenue that otherwise would have been generated is lost. Furthermore, if no market share exists and clients are not found for the gas products, the facility will be forced to close due to a lack of revenue. The operating costs of these facilities will depend on (1) costs and quantities of labor used, (2) cost and quantities of utilities and expendable supplies needed to operate the facility, and (3) the capital costs for construction of the facility (Clark and Rogoff 2010).

Disadvantages exist for PG plants, especially in relation to feedstock size, electricity requirements, and cost issues (Loghin 2008; Yang et al. 2011). It is important to note that pretreatment is a key issue with respect to thermochemical processing. In some cases, further research in this area will be required in order to make the technology viable for specific wastes. A large portion of electricity generated is necessary for the operation of the plasma torches. This leads to a net reduction in electricity generation from the facility. It can vary significantly and depends largely on the throughput (Yang et al. 2011).

Moreover, the public's negative association with thermal treatment waste facilities is another barrier that needs to be overcome. In addition, smell, noise, and visual aesthetic complaints are fairly common from affected community members after waste management facilities have been installed.

15.8 Conclusion

The utilization of PG technology may be expanded in the future with continuing improvements in the technology. It is important to obtain a better understanding of this technology and its potential impacts on the environment, the economy, and existing markets. Besides, evaluations show that syngas production through PG is advantageous over other thermochemical techniques because PG is energy-efficient and environmentally friendly technology. Moreover, current research activities aim to improve PG control and therefore the performance of the process, which indicates the growing economic potential of plasma gasification in the coming decades over yet established thermochemical techniques.

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Natural Gas Hydrates: Possible Environmental Issues

16

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Abstract

During the past 50 years, there has been a growing awareness of environmental issues related to energy technologies and natural resource utilization. A growing global population demands augmenting amounts of energy and goods without big discovery of conventional resources (apart from Zohr and Glafkos offshore fields in Mediterranean Sea, Egypt, and Republic of Cyprus, respectively); leading companies and countries turn their interest in unconventional resources such as shale oil, shale gas, and gas hydrates. Although gas hydrates are assumed part of the alternative energy sources of the future, they exhibit possible environmental risks for both the marine ecosystem and atmosphere environment. This chapter presents the fickleness of methane hydrate (MH) that either takes place naturally or is triggered by anthropogenic activities. Furthermore, it explains the climate change (methane discharged to the atmosphere has 21 times more global warming contingent than carbon dioxide) and the sea acidification (more than half of the dissolved methane retains inside seafloor by microbial anaerobic oxidation of methane) caused by methane hydrate release. Moreover, it presents the seafloor instability when methane hydrated block sediments due to augmentation of temperature or pressure difference. Finally yet importantly, environmental risks and hazards during the operation of production and drilling hydrate reservoirs occupy a significant position in the presentation of this research.

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Keywords
Climate · Energy · Environment · Natural gas hydrates

16.1 Introduction

Worldwide demand for energy is bound to rise substantially in the following periods as the human population expands. Referring to the case of US DOE 2016 International Energy Outlook, the global energy consumption will increase from 549 quadrillion BTU in 2012 to 815 quadrillion BTU in 2040, nominating 48% increase. The main contributors to this rise in demand are non-OECD developing economies, namely, China and India, where demand is predicted to augment by 112% between 2010 and 2040 (E.I.A Annual Energy Book 2013). While the expectation is that renewables and nuclear source can yield more energy as time advances, the amount produced is probably still far from meeting the huge augmentation in energy demand. By 2040, the projections indicate that more than 76% of energy will be of the carbon-based source (gas, oil, and coal), despite the expansion in other renewable sources (Exxon Mobil Outlook 2014). Of these three carbon-based energy sources, natural gas is projected to have the highest rate of increase (1.7% on yearly basis) in comparison with the other fossil energy sources (0.9% p.a. for liquid fuel and 1.3% p.a. for coal) (I.E.A World Energy 2013).

Approximately 80% of worldwide energy request is met by unconventional sources. Gas hydrates (GH) will play a leading role in the future (I.E.A World Energy 2011). Natural gas hydrates (NGH) are natural gas resources which have stayed stationary for millions of years until they have been found since the 1960s (Makogon 1965; Makogon et al. 2007). These icelike solid compounds, which contain hydrocarbons, are existent in permafrost and marine environments. Gas hydrate (GH) resources are distributed more diversely and are present in greater quantities than conventional and other unconventional resources combined, which led various research groups around the globe to take interest in the subject (Merey and Longinos 2018a, b). Natural gas hydrates (NGH), commonly called clathrates, are crystalline compounds that take place when water forms a cage-like structure around small-size gas molecules (Sloan 1991). Natural gas hydrates are nonstoichiometric solid compounds and they are formed when the components come into contact at high pressure and low temperature (Sloan 2003). Gas hydrates are composed of water and mainly the following gas components: methane, ethane, propane, isobutene, normal butane, nitrogen, carbon dioxide, and hydrogen sulfide (Sloan 1991). Makogon clarified the methane hydrate formation reaction as

$$\underset{(\text{Methane})}{CH_4} + \underset{(\text{Liquid})}{N_H H_2O} \leftrightarrow \underset{(\text{Hydrate})}{CH_4.nH_2O} + \Delta H_1 \quad (16.1)$$

$$CH_4 + N_H H_2O \leftrightarrow CH_4.nH_2O + \Delta H_2 \quad (16.2)$$

where N_H is the hydration number approximately equal to 6 for methane hydrates (Sloan and Carolyn 2008). The hydrate formation reaction is an exothermic procedure, which produces heat, while the hydrate dissociation reaction is an endothermic process, which engrosses heat. The heat of configuration of methane hydrate from methane and liquid water is $\Delta H_1 = 54.2$ kJ/mol, and the heat of configuration of methane hydrate from methane and ice is $\Delta H_2 = 18.1$ kJ/mol (Grover 2008).

In 1778, Sir Joseph Priestley produced the first factitious hydrates. Sir Priestley noticed that there was an enhanced "ice" configuration during the time that cold water came into association with sulfur dioxide (Makogon 1997). After 20 years from Sir Joseph Priestley's factitious hydrates, in 1810, Sir Humphry Davy reported on chlorine hydrates as a form of solid water. Davy's evenly well-known assistant, Michael Faraday, also perused the hydrate of chlorine, and in 1823, Faraday mentioned the composition of the chlorine hydrate. Nevertheless, his outcome was not correct; it was the first time of determining the composition of a gas hydrate (Caroll 2009). GH became a significant subject of economic interest in the 1930s when their contingency to clog gas and oil in pipelines became conspicuous (HammerSchmidt 1934; Wilcox et al. 1941).

Concerning the GH fields, the Russian scientists measured a large amount of CH4-rich gas hydrate that supposedly existed in both permafrost regions (Makogon 1965) and marine sediments (Makogon et al. 1971). The first GH field was discovered in Siberian permafrost and then followed by discoveries in Caspian and the Black Sea in 1974 (Makogon 1997). Studying gas hydrates started to be significant due to the augmentation of energy prices in the 1970s. Table 16.1 presents the basic stages of gas hydrate discovery and posterior evolvement (Makogon 2010).

On the other side, there are some physical properties of GH that differ from those of ice. These properties are mechanical strength, heat capacity, thermal conductivity, etc. Table 16.2 compares the physical properties of the two most common hydrate structures with those of liquid water and ice (Koh et al. 2011).

Table 16.1 Achievements on different aspects of hydrates

Period	Achievements
1778	Priestley acquired SO_2 hydrate in the laboratory
1811	Davy obtained Cl_2 hydrate in a laboratory and named it to hydrate
1934	Hammer Schmidt perused gas hydrates in industry
1965	Makogon showed that natural gas hydrates exist in nature and represent an energy resource
1969	Official registration of scientific discovery of NGH
1969 (24 December)	Start of gas production from the Messoyakha gas hydrate deposit in Siberia
1990s	Initial characterization and quantification of methane hydrate deposits in deep water
2000s	Attempts to quantify location and abundance of hydrates begin. Large-scale attempts to exploit hydrates as fuel begins

Adapted from Makogon (2010)

Table 16.2 Physical characteristics of gas hydrates compared with those of ice (Koh et al. 2011)

Property	Water	Ice Ih	Structure I (sI)	Structure II (sII)
Thermal conductivity λ ($Wm^{-1} K^{-1}$)	0.58 (283 K)	2.21 (283 K)	0.57 (263 K)	0.51 (261 K)
Thermal diffusivity κ ($m^2 s^{-1}$)	1.38×10^{-7a}	11.7×10^{-7a}	3.35×10^{-7}	2.6010^{-7}
Heat capacity Cp ($Jkg^{-1} K^{-1}$)	4192 (283 K)	2051 (270 K)	20,319 (263 K)	2020 (261 K)
Linear thermal expansion at 200 K (K^{-1})	–	56×10^{-6}	77×10^{-6}	52×10^{-6}
Compressional wave velocity Vp (kms^{-1})	1.5	3.87 (5 Mpa, 273 K)	3.77 (5 Mpa, 273 K)	3.821 (30.4–91.6 Mpa, 258–288 K; C_1-C_2)
Shear wave velocity Vs (kms^{-1})	0	1.94 (5 Mpa, 273 K)	1.96 (5 Mpa, 273 K)	2.001 (26.6–62.1 Mpa, 258–288 K; C_1-C_2)
Bulk modulus K (GPa)	0.015	9.09 (5 Mpa, 273 K)	8.41 (5 Mpa, 273 K)	8.482 (30.4–91.6 Mpa, 258–288 K; C_1-C_2)
Shear modulus G (GPa)	0	3.46 (5 Mpa, 273 K)	3.54 (5 Mpa, 273 K)	3.666 (30.4–91.6 Mpa, 258–288 K; C_1-C_2)
Density ρ (kgm^{-3})	999.7 (283 K)	917 (273 K)	929 (273 K)	971[b] (273 K); 940 (C_1-C_2-C_3)

[a]Calculated from $k = 1/(r*Cp)$
[b]Calculated from Sloan (2003)

As methane hydrates are able to comprise between 150 and 180 v/v at standard temperature and pressure conditions, they provide distinct gas storage characteristics. The subsequent discovery of hydrate self-preservation, a property which permits hydrates to stay metastable under the conditions of some degrees lower than the ice point, while at atmospheric pressure (Sloan 2003; Makogon 1997), has influenced scientists to peruse the possibility of storing and transporting gas in the form of hydrates. Such research was conducted for the initial time by Gudmundsson et al. (1995) in the early 1990s; then, various scholars have published results in this area of research (Koh et al. 2011).

Gas hydrates look like compact ice and can be burnt, and they usually smell like natural gas. One cubic foot of methane hydrate can compress around 164 ft^3 of methane at standard pressure P and temperature T (Makogon 1994). The density for GH varies, firstly according to the composition of the gas, secondly according to temperature T, and finally due to pressure P, which they are used to form hydrates. The values of density are measured from 0.8 to 1.2 gm/cm^3 (Makogon 2007) (Table 16.3).

Due to the fact that the density of GH is 0.920 gr/cm^3, methane hydrate is less dense than the water. The cavities in the hydrate crystal for the degree of filling depended on the hydrate texture. The morphologies for GH can be varied due to gas composition and crystal growth conditions (Makogon 1981). The hydrate dissociation is an endothermic reaction. Figure 16.1 shows the heat of dissociation of different hydrates (Makogon 1997) (Table 16.4).

Table 16.3 Properties of different hydrates (Makogon 1997)

Gas	Formula of hydrate	Hydrate density@273 K(gr/cm^3)
CH_4	$CH_4.6H_2O$	0.910
CO_2	$CO_2.6H_2O$	1.117
C_2H_6	$C_2H_6.7H_2O$	0.959
C_3H_8	$C_3H_8.17H_2O$	0.866
C_4H_{10}	$iC_4H_{10}.17H_2O$	0.901

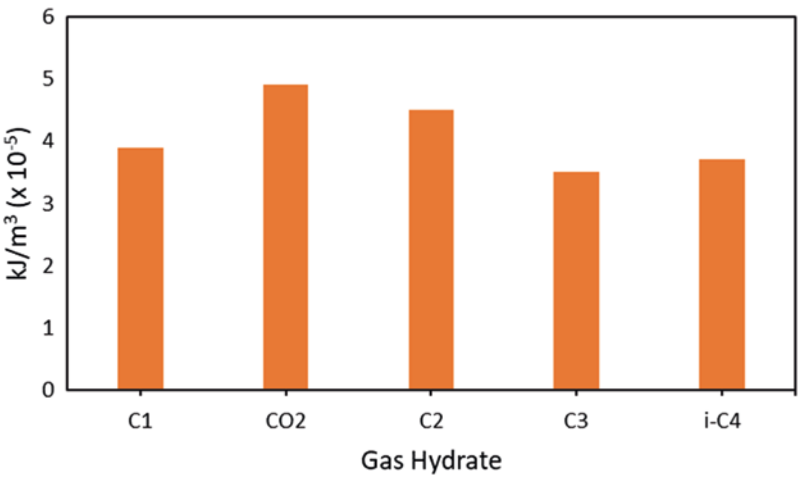

Fig. 16.1 Heat dissociation of different hydrates. (Adapted from Makogon 1997)

16.2 Hydrate Structures

Water molecules that synthesize the cavities, which are constituted of pentagonal and hexagonal faces, mold hydrates. The combination of alterative faces helps for the formation of different hydrate structures to the fact that geometric structures are significant to comprehend the nature of hydrates. Two structures (types) of hydrates are the most common in the chemical and petroleum industry, and these are the structure I (sI) and structure II (sII). Another structure (type) that is less common than the two previous structures is the structure H (Sloan and Carolyn 2008).

The structures (sI, sII, and sH) are described by the parameters of Table 16.5. The small cage (SC) of sI is connected in space by the vertices of the cages. In the small cage (SC) of structure sII, the faces are shared. The spaces for both of the structures between the SC are formed by a large cage (LC). As far as it concerns the structure sH, the face sharing occurs in two dimensions such that a layer of SC connects to a layer of medium and large cages (Sloan and Koh 2007; Ribeiro and Lage 2008). The three structures of gas hydrate embody alterative guest molecules into a single cell but, sH needs two different-sized molecules to form: One small molecule as a helping gas such as methane accomplishing the small cage and a large molecule (Sloan 1990).

Table 16.4 Physical properties of gas hydrates compared with those of ice (Koh et al. 2011)

Property	Water	Ice Ih	Structure I (sI)	Structure II (sII)
Thermal conductivity λ ($Wm^{-1} K^{-1}$)	0.58 (283 K)	2.21 (283 K)	0.57 (263 K)	0.51 (261 K)
Thermal diffusivity κ ($m^2 s^{-1}$)	1.38×10^{-7a}	11.7×10^{-7a}	3.35×10^{-7}	2.60×10^{-7}
Heat capacity Cp ($Jkg^{-1} K^{-1}$)	4192 (283 K)	2051 (270 K)	20,319 (263 K)	2020 (261 K)
Linear thermal expansion at 200 K (K^{-1})	–	56×10^{-6}	77×10^{-6}	52×10^{-6}
Compressional wave velocity Vp (kms^{-1})	1.5	3.87 (5 Mpa, 273 K)	3.77 (5 Mpa, 273 K)	3.821 (30.4–91.6 Mpa, 258–288 K; C_1-C_2)
Shear wave velocity Vs (kms^{-1})	0	1.94 (5 Mpa, 273 K)	1.96 (5Mpa, 273 K)	2.001 (26.6–62.1 Mpa, 258–288 K; C_1-C_2)
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Density ρ (kgm^{-3})	999.7 (283 K)	917 (273 K)	929 (273 K)	971[b] (273 K); 940 (C_1-C_2-C_3)

[a]Calculated from $k = 1/(r*Cp)$
[b]Calculated from Sloan and Carolyn (2008)

Structure I gas hydrates comprise 46 water molecules per unit cell arranged in two dodecahedral voids and six tetrakaidecahedral voids which can accommodate at most eight guest molecules. The hydration number ranges from 5.75 to 7.67. Structure II gas hydrates comprise 136 water molecules per unit cell arranged in 16 dodecahedral voids and eight hexakaidecahedral voids, which can also accommodate up to 24 guest molecules with hydration number 5.67. The rarer structure of gas hydrates, which contain 34 water molecules per unit cell arranged in three pentagonal dodecahedral voids, two irregular dodecahedral voids, and one icosahedral void, can accommodate even larger quest molecules such as isopentane. The hydration number of sH is 5.67 like sII (Longinos 2015; Koh et al. 2011).

16.3 Location of Gas Hydrates

After 1920 when the pipelines started to transport methane from gas reservoirs, there was more knowledge about hydrate applications. In low temperature, there was a plug in pipelines which sometimes put obstacles for the gas to flow through them. In the beginning, these blocks were construed as frozen water. The correct description about these blocks was given in the 1930s, and it was hydrate. About

Table 16.5 Structures of gas hydrate cells

Structure	I		II		H		
Crystal system	Cubic		Cubic		Hexagonal		
Space group	Pm3n (no. 223)		Fd3m (no. 227)		P6/mmm (no. 191)		
Ideal unit cell	$2(5^{12})6(5^{12}6^{2}) \times 46H_2O$		$16(5^{12})8(5^{12}6^{4}) \times 136H_2O$		$3(5^{12})2(4^{3}5^{16}6^{3}) \times 34H_2O$		
Ideal hydration number	5.750		5.667		5.667		
Cages	Cages		Cages		Cages		
	Small	Large	Small	Large	Small	Medium	Large
Average cavity radius (A)	3.95	4.33	3.91	4.73	3.94	4.04	5.79
Variation in radius (%)	3.4	14.4	5.5	1.71	4.0	8.5	15.1
Water molecules per cavity	20	24	20	28	20	20	36

Space group reference numbers from the International Tables for Crystallography (Sloan and Koh 2007)

98% of the GH resources are concentrated in marine sediments, with the other 2% beneath the permafrost. The majority of occurrences of GH have been found by scientific drilling operations, and the inferred GH accumulations have been clarified by seismic imaging (Boswell et al. 2010).

In 1946, Russian researchers nominated that the conditions and resources for hydrate formation and stability exist in nature, in regions covered by permafrost (Makogon 1997). After this proposal from the Russians scientists, there was a discovery of the naturally occurring hydrates. This fact took place in 1968 at Byrd Station in western Antarctica where ice cores including hydrates were educed during scientific drilling program (Miler 1969). In the 1970s, researchers after drilling programs explored hydrates taking place amply in deep water sediments on outer continental margins. Lately, hydrates have been noticed on the seafloor, and in one occasion, hydrates were located in the surface of a fishing net (Riedel et al. 2014). The last appearance of hydrate on the surface in sediments happened due to gas seeps which are also called cold vents such as those in the Gulf of Mexico (GoM) and off the Pacific Coast of Canada. Scientists noticed that hydrates can take place in many places of the world and the depth range varies from 100 to 500 m beneath the seafloor. Important hoardings of hydrates have been defined on North Slope of Alaska, in northern regions of Canada, in the Gulf of Mexico (GoM), in Japan, in China, in India, and in South Korea (offshore reservoirs) (Brook et al. 1986; Merey and Longinos 2018a, b, c).

The four important plays that hydrates could be discovered were sand-dominated plays, fractured clay-dominated plays, huge quantities of gas hydrate formations exposed at seafloor, and low-concentration hydrates disseminated in a clay matrix. It is also found that hydrates exist in fracture fillings in clay-dominated systems in shallow sediments (Merey and Longinos 2018a, b, c). The NGH in marine sediments are regulated by the hoardings of particulate organic carbon (POC) which is microbial transformed into methane, the thickness of the GH stability zone (GHSZ) that methane (CH_4) can be ensnared, the sedimentation rate (SR) that checks the time that POC and the produced methane(CH_4) stays within the GHSZ, and the distribution of CH_4 from deep-seated sediments by ascending pore fluids and gas into the GHSZ (Pinero 2012).

16.4 Gas Seepages

The seeps of natural gas are caused by upward migration of light hydrocarbons which formed in source rocks before being confined in reservoirs. Seeps include mud volcanoes, dry seeps, and springs rich in CH_4. They offer invaluable knowledge for hydrocarbon exploration and geology, structural and tectonic research, and environmental concerns, for example, geohazards and greenhouse gas budget. The impetus for seeps is pressure gradients in hydrocarbon subsurface accumulations. These are known historically to being crucial driving forces behind hydrocarbon exploration worldwide (Rhakmanov 1987). Additionally, they aid hydrocarbon utilization in the area of geochemical and pressure alteration assessment in fluid extraction. They are also vital for defining the petroleum seepage system (Abrams 2005).

Both tectonic discontinuities and rock formations with enhanced secondary permeability can be identified effectively by the existence of seeps. They provide knowledge of the location and depth of gas-bearing faults. Due to its sensitivity to seismic activity, mud volcanism, particularly, has been examined comprehensively (Mellors et al. 2007). Studies conducted on ecological problems, such as aquifer contamination and underground gas storage feasibility, could benefit from seeps. However, they have been identified as a hazard for humans and constructions also (Etiope et al. 2006). When CH_4 concentrations touch the explosive levels (5–10% in the presence of air), sudden flames and explosions are likely to happen in gas-rich environments, such as soil and boreholes. The combination of CH_4 and hydrogen sulfide (H_2S) (e.g., in salt diapirism zones) gives seeps the ability to be toxic and, sometimes, fatal under certain conditions. Another cause of hazards is highly fluid mud, particularly in mud volcanoes. It can promote the development of "quicksand" which is known to present risks for fauna and human beings.

Buildings and infrastructures can be impaired by seeps and mud volcano plumbing in two mechanisms: gas pressure buildup under the soil and overall degrading of geotechnical characteristics of soil foundations. To conclude, both onshore and offshore seepage, including microseepage, are among the main greenhouse gas sources, due to the estimations yielding that seepage is the second most significant natural source of CH_4 in the atmosphere, after wetlands (Etiope and Milkov 2004). Identification of methane source (i.e., biogenic from carbonate reduction, biogenic from acetate fermentation, thermogenic, inorganic) offers information regarding the environment and process behind its formation. With this knowledge, seepage gases can be utilized for tracing hydrocarbon reservoirs, as well as indicating geodynamic processes, hazards, and their role in worldwide changes (Etiope and Klusman 2002).

Visible manifestations (macroseeps) could be formed by gas seepage. These, in general, disturb soil settings and surface morphology. More often, we have microseepage, which is invisible yet prevalent, diffuse emission of light hydrocarbons from the soil. It can be distinguished using standard analytical procedures. Microseepage is capable of reducing the methanotrophic consumption taking place in dry and/or cold soils. Hence, it leads to positive fluxes of methane to the air through large areas (Etiope and Klusman 2008). Both macro- and microseepage normally result from gas advection. The latter is driven by pressure gradients and permeability (Darcy's law) through faults, fractures, and bedding planes (Brown 2000). Advection comprises single-phase gas movement and two-phase flows, as density-driven or pressure-driven continuous gas-phase dislocating water in saturated fractures, the floating motion of gas bubbles in aquifers and water-saturated fractures, in the form of slugs or microbubbles (Etiope and Martinelli 2002). The slow gas motion driven by concentration gradients, known as diffusion (Fick's law), is dominant only in long-term and small-scale gas flow through more homogeneous porous media, for example, primary hydrocarbon migration from source rocks to reservoirs or into nearby pools.

Per se, we cannot invoke it for source seeps. Macroseeps have three main subcategories: mud volcanoes, water seeps, and dry seeps. Mud volcanoes emit a three-phase (gas, water, and sediment) mix (Dimitrov 2002). Water seeps discharge a profuse gaseous phase, alongside water release (bubbling springs, groundwater, or hydrocarbon wells), in which the water can have a deep origin and there is probability of it being interacted with gas through its rise to the surface. Dry seeps have only gaseous-phase emissions, such as gas vents from outcropping rocks or via the soil horizon or by river/lake beds (Etiope et al. 2009).

16.5 Environmental Impacts of Gas Hydrates

In the last decades, the attention of both scientific and political community on climate alteration has augmented (Sanjairaj et al. 2012; Pryor and Barthelmie 2010). Marine ecosystems have accepted environmental impacts due to decrease of oxygen concentration dissolved and the augmentation of sea temperature (Deutsch et al. 2015). Both governments and industrial sector must face the treatment of climate change dominantly, and more financial backing and coating in green technologies must be supported (Watts et al. 2015). Furthermore, EU countries agreed to have a 20% decrease in their greenhouse gas emissions by 2020 compared to 1990 (Roos et al. 2012).

Nevertheless, there are limited studies targeting the policies concerning GH-urged climate alteration and recommended solutions. It is obvious that until GH become an attainable energy source, it will be needed to overcome different present difficulties (Sanjairaj et al. 2012). Any try of a production test of GH could be a contingent danger for both marine and atmospheric environment (Hautala 2014). The process of releasing methane gas from hydrate in either marine environment or the atmosphere by anthropogenic actions or natural causes may create environmental impacts on component poise, sea environment, and even global climate alteration. In addition to the devolution into a gas from solid-phase GH and the continued reduced aid to the sand grains that take place in the surroundings, it creates seafloor instability and sometimes submarine landslides (Zhao et al. 2017).

Anthropogenic activities may cause the instability of methane hydrates, or methane hydrates may dissociate naturally. For example, a little temperature rise in the deep sea can cause methane hydrates to start dissociating. Temperature rise that occurs in deep parts of the ocean might trigger surface climate alteration and the outcome being the release of crucial amounts of methane from GH. Therefore, these result in the increase of carbon in the atmosphere (Schiermeier 2008). Besides temperature alterations in the high depth of the sea, the ocean motion encourages the release of gas-hydrate-derived methane (Thomsen et al. 2012). The period and strength of wobbling currents strongly influence methane seepage. Actually, motions produced by winds, daily rock waves, or internal semi-quotidian tides create the eruptions of intense bottom current. Typical spatial scales over 100 km and time periods up to several weeks characterize the inertial motions (Jordi and Wang 2008).

According to Thomsen et al., methane dissolution rates are changing linearly with friction velocity (Lifshits et al. 2018). Long periods (100–1000 years) of ventilation take place in the high depth of the sea. Hence, it takes a new equilibrium methane hydrate inventory 1000–10,000 years. Likewise, the fraction of methane from the bottom of the sea that attains the atmosphere is precarious and depends on the function of transportation like bubbles (Boldyreff 2016).

There is an abundant amount of methane hydrate beneath permafrost and seabed. Yet, this potential energy source can be a major trigger of global warming. Methane has a global warming potential (GWP) of 21, which means that a tonne of methane, when dissociated into the atmosphere, has the warming potential 21 as compared to a tonne of carbon dioxide released over 100 years which has a warming contingency of 1 (Hope 2006). Because of the higher quantity of carbon dioxide compared to methane in the atmosphere, methane has less saturated infrared radiation bands (Change IPOC 2007). Thus, a high quantity of methane which is released naturally to the atmosphere might be an intrinsic parameter of global warming. Organic materials which are agglomerated from the photosynthesis both in terrestrial and in marine environments are degraded and lead to the formation of methane. Due to the unsteadiness of methane hydrates beneath the earth, methane hydrate (MH) is essentially vulnerable to be released. The vast quantity of methane which can be released unexpectedly might attenuate the present climatic conditions.

Due to climate alterations, there is a global elevation of temperature which might lead to the deduction of permafrost in the Arctic and the release of stored methane gas. Hence, the deterioration of the climate change is attributed to the greenhouse gases (i.e., methane). Actions could be taken, firstly, to audit the escape of methane from hydrates and, secondly, to capture gas released, for the removal of the phenomenon of global warming. A 3 °C positive temperature change could release 35–94 GtC of methane gas, which may increase 12-fold the methane percentage in the atmosphere. As an outcome of this, there would be an extra 0.5 °C of global warming (Saxton et al. 2016).

Methane dissociation from hydrates in the sea areas might lead to sea acidification and oxygen reduction. Microbial anaerobic oxidation of methane (AOM) could retain more than 50% of the dissolved methane within the seafloor (Knittel and Boetius 2009). AOM transforms oxygen and methane into carbon dioxide, which is the main substance of affecting the oceanic pH (Biastoch et al. 2011). Both induced methane and anthropogenic carbon dioxide are the main factors for the deterioration of the oceanic acidification (Solomon 2007). Adverse effects on the sea environment may be imposed by oceanic acidification. When the pH in the marine system is lowered, fertilization and reproduction of sea species may be influenced. This will lead to a decrease in species population, as well as a calcification at larval and settlement stages. Shellfish such as oyster, clams, and corals can be influenced by the higher partial pressure of carbon dioxide (Kurihara 2008).

Through the formation of methane hydrate within the sediment pore spaces, there is immobilization of solid-form methane and water. The imposing stresses of the sediment emerge because water cannot be expelled into it. Due to the augmentation of the temperature or the pressure lessening, methane hydrate solidifies the sediment and becomes erratic. The hydrate-bearing sediments will be consolidated by gas mixture, and liquid water will be dissociated by the hydrate. Then, the resulting methane release will lead to the formation of a zone with a low shear strength (Dou et al. 2011). Subsequently, deformation of the seafloor exists, which results in a submarine landslide, an earthquake beneath the seabed, and even a tsunami. Furthermore, it is supported that every mass failure produced by the catastrophe of continental slope is correlated with one or another way with the diminishment of sea level due to climate change.

The quick diminishment of sea level creates instability to gas hydrate deposits, and this leads to triggering the slope malfunction and the glacial mass transport of deposits (Thomsen et al. 2012). The slope failure and the glacial mass transport of deposits could be triggered by the quick change of sea level destabilizing gas hydrate reservoirs in the mainland (Maslin 1998). Moreover, in hydrate reservoirs in oceans underlain by sediment comprising gas hydrate, the diminishment of sea plump could commence the dissociation along the base of gas hydrate, which successively would congest the escape of large volumes of gas into the sediment augmenting the pore-fluid pressure and diminishing the slope firmness (Zhang et al. 2016).

16.6 Gas Hydrate Environmental Issues in Drilling Operations

Nowadays worldwide, there is quite enough knowledge about drilling conventional gas and oil wells both in the shoreward and in seaward environment. Nevertheless, trying to drill a gas hydrate well needs knowledge, which is not quite existent yet. Researchers and engineers should estimate how to drill a gas hydrate well without enough features. Hence, it is obvious that the function of drilling gas hydrate reservoirs may be hazardous. Several essential dangers are observed: (1) When hydrate is formed, it blocks the borehole; (2) when gas hydrates are dissociated abruptly, it creates blowout; (3) when gas hydrates are separated abruptly, there is danger of slope failure; and (4) when gas hydrates are separated, there is difficulty in both instability of the wellbore and danger in wellbore subsidence because of the loose sediments (Tan et al. 2005).

When the procedure of drilling starts, the management of temperature and pressure in the wellbore must be audited to limit reservoir's hydrate dissociation together with annulus mud. Another challenge during drilling operations in hydrate reservoirs is the correct casing design to resist high values of pressure. Furthermore, when fracture gradient and pore pressure are very close (there are limited window margins), there is a high possibility for kick or formation fracture risks, which lead to the collapse of the well. Finally yet importantly, in drilling operations in gas hydrate reservoirs, there must be frequent good control for gas kick circulation or abrupt gas flow for unconsolidated formation (Motghare and Musale 2017). All these challenges may create huge environmental problems especially in offshore locations (95% of hydrate reservoirs) with countless consequences on the sea chain.

More specifically, hydrate drilling risks can be separated into drilling and testing processes. In a casing program, the well part must be drilled with a drilling fluid that provides high relative density, which will give the maximum wellbore pressure and the highest possibility for hydrate risk. The intensity of heat present and pressure field in the wellbore at alternative pumping proportions of drilling fluid can be prognosticated by the assistance of heat and mass transfer model in which parts such as heat devolution between the fluid in the drill string, the wall of the drill string, the fluid in the annulus, and the ambient environment are examined. Due to geothermal gradient at the starting state, the temperature in the wellbore during drilling process was acquired through time-repetitive estimation along the converse flow movement of drilling fluid up to the heat in the wellbore of the field arrived approximately in a stable situation, although the pressure inside the reservoir was estimated due to fluid friction loss in drill string and annulus and the pressure difference (decrease) at the drill bit.

At the wellbore temperature of the reservoir at alternative drilling fluid pumping values, the intersected part between the wellbore temperature curve and the hydrate temperature curve is the good section with hydrate risk. It is also known that at alterative drilling fluid pumping rate, the wellbore section is different. Hence, the good section at water depth between specific meters is under hydrate risk, and the highest value of undercooling temperature is at high temperature and takes place at seabed mud line (Bangtang et al. 2014; Bo 2007; Yonghai et al. 2008).

As far as it concerns the testing process when the well arrives at the design depth, the casing will be put for the cementing process, and the drill string will be utilized for gas production testing. At the time that there is perforation at the correct layer, the testing fluid of the drill string will be dislocated by the natural gas and blown to the surface connected with a short amount of formation water under throttle control. At another time, the pressure field and wellbore temperature during testing of alternative gas values and water contents were prognosticated by the use of heat and mass transfer model of deepwater production well. The wellbore pressure is estimated by the use of Orkiszewski method, while the estimation of wellbore temperature regards the heat transfer between the fluid in test string and annulus, the cement sheath and the rock below seabed, and seawater above seabed, while the whole temperature value can be estimated by using the discrete coupling formula of pressure and temperature reservoirs from the bottom to the wellhead (Zhang et al. 2014).

It can also be noticed that if it's shut down long enough during testing, the wellbore temperature will be equal as the ambient temperature. At the initial moment of the testing, the pressure in the test string augmented slowly but surely, when the natural gas changes the testing fluid from downhole to the surface, but the highest undercooling temperature in the test string will not go up to the case when the test is paused with the test string filled with natural gas. Through throttling open flow, the test string will be loaded with natural gas and a small amount of formation water. Augmentation in both gas values and water concentration is positive for decreasing pressure and increasing temperature in the wellbore, which will lead to shorten the well part with hydrate risk (Yang et al. 2013).

Two field examples of hydrate problems in the face of drilling activities took place in US west coast in the depth of 350 m and in the Gulf of Mexico in 950 m, respectively. In the initial occasion of 350 m drilling operation, gas inserted in the well and the kill process endured 1 week, and then, hydrates were generated in riser, choke, and kill lines and blowout preventer (BOP). The second occasion of 950 m took place in the Gulf of Mexico where an elongated well control process ensued from malfunction of the BOP to work suitably due to hydrates. As an outcome, unpropitious implications of hydrate formation in the phase of well control process took place such as the plugging of kill and choke lines which obstruct well circulation. The audit of well pressure below the blowout preventers (BOPs) is obstructed due to the plugging formation at or below BOPs. The drill string rotation is hindered due to hydrate formation plugging the riser, BOPs, or casing. The total aperture of BOP is blocked from hydrate formation plugging the cavity of a closed BOP (Baker and Gomez 1989).

16.7 Conclusion

Worldwide demand for energy is bound to rise substantially in the next decades as human society expands. Referring to the case of US DOE 2016 International Energy Outlook, the global energy consumption will increase from 549 quadrillion BTU in 2012 to 815 quadrillion BTU in 2040, indicating a 48% increase. Natural gas hydrates may be considered as both a promising future energy source and a possible contributor to the global climate change. The relationship between gas hydrates and climate is not clear; however in geological history, there were clear facts showing that high amount of release of methane gas from hydrates had a probable potent effect on global climate. This fact can be easily understood. Although the residence time of gas hydrate release is limited in the atmosphere over the lifetime, methane as gas compared to carbon dioxide is around 20 times more effective in terms of its total greenhouse contamination. Moreover, the ongoing methane release in sea environments may be spliced to alter the climate with the objection that the historical data of these inferences is little and needs verifications.

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