Environmental sustainability: challenges and viable solutions

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Abstract
Since last century or so anthropogenic activities have intensely metamorphosed the earth’s ecosystem and resulted into major environmental changes. Widespread interference of human related activities have resulted in major problems including environmental pollution, land degradation, global warming/climate change, paucity of potable water supply and biodiversity loss. These issues have directly affected the quality and sustainability of the ecosystems. In addition, these activities have resulted in loss of habitats resulting in mass extinction of species which in itself is a matter of great concern. Studies and data clearly show that if present trends continue the conditions are expected to worsen in the coming time and human civilization itself will be in trouble. To minimize this crisis, possible green solutions like use of microbes and biotechnological tools are gaining importance and need further attention in order to lessen or remediate the harmful effects of anthropogenic activities thus ensuring environmental sustainability.

Keywords Environmental sustainability · Anthropogenic activities · Climate change · Greenhouse gases · Pollution · Microorganisms · Bioremediation · Biotechnology · Biofuels · Sustainable agriculture

Introduction
Earth is the only celestial body in the universe where life is known to exist and that too with such a huge diversity. However, it is now becoming more and more inhabitable for most of the species as indicated by steep decline in diversity of flora and fauna. The main reasons behind the worsening conditions for life on earth are the anthropogenic activities. The human interference has resulted in increase in concentration of greenhouse gases (GHGs), climate change, degradation of land, pollution of air water and soil, depletion of non-renewable resources, loss of biodiversity, accumulation of harmful recalcitrant chemicals and several related issues.

Since the last few decades the impact of environmental problems has been highlighted at several forums. In 1960s, the United Nations (UN) discussed the environmental costs of growth-centered or conventional development. In the report ‘Our Common Future’ (known as the Brundtland Commission), released in 1987 by the World Commission on Environment and Development (WCED), it was stated that development is only ‘sustainable’ if it ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED 1987). WCED global agenda was an initiative to work on sustaining the planet for better future. Similarly, the UN Conference on the Environment in Stockholm and on Environment and Development (UNCED) in Rio de Janeiro (1992) accepted that the un-sustained human activities towards environment will cause huge, irreversible damage to life on earth (http://www.un.org/geninfo/bp/enviro.html). The UN Agenda 21 was to promote sustainable development undertaken at the Earth Summit held at Rio de Janeiro. The agenda formed the basis for a “global partnership” to encourage cooperation among nations for sustaining life on earth by protecting the environment while simultaneously resulting in growth. For reducing the climate change, countries of the world adopted the Paris
Agreement (COP21) in 2015 to work out and limit global temperature rise below 2 °C. However, very recently United States (US) pulled out of the Paris agreement citing its own reservations putting the whole accord in jeopardy. Paris agreement was advanced further by UN Framework Convention for Climate Change in Bonn, Germany in 2017 to achieve the targets and for attaining sustainable goals (UNFCCC 2017). In Millennium Development Goals (MDGs), out of the 8 goals, that all UN member states had agreed to try to achieve by the year 2015, Goal 7 or MDG7 was to ensure “environmental sustainability” (http://www.fao.org/sustainable-development-goals/mdg/goal-7/en/). Out of all the targets only a miniscule has been achieved so far. To succeed the MDGs, the UN Sustainable Development Goals (SDGs) were launched in 2015 which are related to climate change, innovation, sustainable consumption, elimination of poverty, and creation of peace and security.

Indeed, the state of knowledge for defining the term “environmental sustainability” is remarkably imperfect and thoughts and considerations of different groups or individuals in various professions show discrepancy. More often, the term exhibits a relationship of economy, society and environment. According to Vezzoli and Manzini (2008) the term “environmental sustainability” refers to systemic conditions where neither on a planetary or regional level do human activities disturb the natural cycles more than the natural resilience allows, and at the same time do not impoverish the natural capital that has to be shared with future generations. The increasing environmental problems faced by the world are mostly in lineation with the increasing human activities. The scenario of land availability, quality environment and biodiversity has been continuously deteriorating with predictions of even worst conditions by 2050. It is imperative to include the ecological and biological aspects to achieve the targets of environmental sustainability, which have been lacking so far. An integrated approach is required at an urgent and continuous basis to curate the earth of anthropogenic issues. Biological approaches have to be the front runners and need to be utilized at maximum to achieve the targets of environmental sustainability. In this review, major environmental issues are discussed in the first half of article, followed by the solutions involving biological approaches so as to achieve environmental sustainability, which have been explored and projected.

Environmental issues

Environmental issues are one of the top priorities of all the governments and researchers around the globe. At present the situation is somewhat grim (Arora 2018a, b). The way things are moving we are going to face several critical issues related to environment some of which are even threatening to the human civilization. Several serious problems related to environment are plaguing the planet at present and these have very serious impact on the biological forms. Most striking issues of the environment are discussed in this section.

Pollution

Environmental pollution is a global menace influencing every nook and corner of the earth. All types of life forms are in one way or the other affected by the impact of pollution. Organisms living at poles or deep under the sea, where humans do not even inhabit are also impacted by the effects of pollution. In the last few decades, various types of pollutants have appeared due to anthropogenic activities, adversely affecting the ecosystems (Rockström et al. 2018). Conditions in developing countries are more debilitating as the rampant industrialization, high rate of deforestation and urbanization are deteriorating the ecosystems. Approximately 92% of pollution-related deaths are reported from the developing countries (Landrigan et al. 2017). Urban locations have become congestion hotspots jeopardizing the mobility and quality of air, water and soil (Solé-Ribalta et al. 2016). According to a UN report, the urban population is expected to double by 2030 (UN 2014). Financial losses due to pollution are estimated to be US$ 4.6 trillion per year accounting for 6.2% of global economic output. Environmental risk factors mainly due to air pollution and non-communicable diseases are driving up health care costs, which consume nearly 10% of global gross domestic product (GDP) (WHO http://apps.who.int/nha/database 2017). In low and high-income countries various types of pollutions can increase annual budget of health-care by 1.7% and 7% respectively (Landrigan et al. 2017). Whereas the actual costs of remediation of natural resources such as water, air and soil are yet to be estimated and worked out.

Each year a wide range of pollutants are released in the environment through industrial emissions. The data reveals that more than 1,40,000 new chemicals and pesticides have been synthesized since 1950 (Landrigan et al. 2017) and only a very few of them like; polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), polyethylene, hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs) have been critically assessed for toxicity. Role of CFCs in ozone layer depletion is very well known. Thankfully, CFCs causing trouble in the ozone layer were expelled by the Montreal protocol (https://www.nasa.gov 2018). However, in the last few years, research on ozone depletion revealed thinning in the lower stratosphere over the non-polar areas (Hansen 2018). Researchers now suspect the role of chemicals used in paint industries to be responsible for ozone depletion in non-polar regions (Carrington 2018). Fossil fuel consumption for supply of energy demand of globe is very high and it is one of the major reasons of
air pollution and global warming which is discussed in subsequent sections.

Plastics are another example of man-made xenobiotic and recalcitrant pollutants which are causing havoc on earth. Plastics are ecological and environmental scourge because of the damaging effects on the ecosystems around the globe. Each year about 79,000 tonnes of plastics are dumped in the Pacific Ocean alone. The ‘great Pacific garbage patch’ floating in the Pacific Ocean is three times the size of France (Pettit 2018). In a very recent report, Wieczorek et al. (2018) declared that 73% of mesopelagic fish caught in Northwest Atlantic Ocean had microplastics in their gut. As mesopelagic fishes are food for a variety of marine animals, there are fair chances of circulation of microplastics through the food chain in the ecosystem. A similar study was also conducted by Borrelle et al. (2017) highlighting risks of plastics on filter feeders in the oceans. Despite the horrible consequences of plastics the production of these hazardous chemicals is still increasing by the minute and earth has become a dumping yard of these non-degradable entities.

Among major anthropogenic activities oil spills are also causing great harm to the marine ecosystems of the planet. Millions of barrels of oil have been dumped into the oceans every year due to offshore oil rigs, damaged tankers and pipelines or accidents (National Research Council 2003; Chang et al. 2014). Oil spilled over the oceans cuts off oxygen supply, prevents the sun’s light from entering the water body and result in accumulation and dispersal of toxic components which cause the death of flora and fauna, reducing population of useful microbes and even extinction of keystone species. Oil spills affect environment at local, regional and global scale with short and long term destruction effects (Liu and Kujawinski 2015). Spilled oil has various types of components such as polar and non-polar, volatile and non-volatile with diverse impacts on the flora, fauna and ecosystem as whole (Nounou 1980). Some mechanical injuries of organisms and habitats are also attributed to oil spills due to physical effects such as coating, smothering and persistence (O’Brien and Dixon 1976; Lee et al. 2015).

Rapid urbanization, industrialization and related anthropogenic activities have been polluting land and water with toxicants such as heavy metals (Yadav 2010). Although addition of heavy metals is natural yet anthropogenic activities are increasing their concentration to exceeding levels (Mishra et al. 2017). Industrial and agricultural wastewater, domestic sewage, spillsages of petroleum hydrocarbons, mining, industrial processes including refineries, metal processing, fossil fuel burning, nuclear power stations, metal corrosion, plastics, textiles, lead based paints, electronic wastes, smelting, use of pharmaceutical chemicals, agrochemicals, waste incineration and vehicle exhausts are the main sources of heavy metals in soil (WHO 2010; Yan et al. 2018). The contamination of heavy metals has been found in both soil and water ecosystems throughout the globe. In Flint (Michigan), North America in 2014, the source of water was changed from Lake Huron to Flint River because of the lead pollution reported in the lake. The problem further contaminated the water source and in January 2016, the President of US declared emergency because of severe lead contamination of drinking water (Wendling et al. 2018). In Karachi, Pakistan, about 89% of sampled drinking water were found to be contaminated with lead exceeding the World Health Organization (WHO) recommended limit of 10 µg/l (Sanchez-Triana 2016). About forty-two rivers in India have been found to be contaminated with toxic heavy metals exceeding the permissible limits (https://weather.com/en-IN/india/pollution/news/2018-05-16-heavy-metal-toxicity-india-rivers). About 10% of China’s total land has been reported as excessively polluted by heavy metals (https://phys.org/news/2011-11-excess-heavy-metals-china.html). Latin America has been marked with most polluted cities of the world and the reason being poorly conducted mining of heavy metals (https://www.conservationinstitute.org/10-most-polluted-cities-in-the-world/). Contamination of mercury (Hg) and other trace elements has been reported in surface soils of Arctic. Parts of Arctic including Svalbard, the Pechenga-Nikkeli district and Siberia have mining activities which lead to contamination of soils with heavy metals (http://www.npolar.no/en/themes/pollutants/the-arctic/sources.html; Halbach et al. 2017). Apart from this, there is recent report showing that even Mount Everest has been polluted with heavy metals with samples showing presence of As and Cd at levels higher than the acceptable limits as decided by US Environmental Protection Act (USEPA) (http://www.dnaindia.com/technology/report-mount-everest-soil-polluted-by-dangerous-levels-of-arsenic-cadmium-1476505). Yeo and Langley-Turnbaugh (2010) reported that the collected samples of soil and snow between 5334 and 7772 m showed high levels of contamination and the expected reason being the transportation of trace elements in the troposphere (mainly from anthropogenic sources) to Mt. Everest.

Climate change and global warming

The climate of the earth is controlled by various factors such as output of energy from the sun, volcanic eruptions, concentration of GHGs in the atmosphere and aerosols. There is no doubt that global climate is changing continuously particularly since industrial revolution. Due to increase in anthropogenic activities such as industrialization, urbanization, deforestation, modern agriculture practices, change in land use pattern and many more the climate change is now occurring at a very fast pace (Mahato 2014). Climate change usually refers to change over time in variables such as precipitation, wind, with temperature as main focus (Parry et al. 2007). Intergovernmental Panel on Climate Change (IPCC)
stated that human influence has been the dominant cause of the global warming since the mid-20th century (Cook et al. 2016). Rate of carbon dioxide (CO₂) emissions and climate change have strong correlation with each other (Davis 2017). Currently climate change is happening mainly due to increased emission and accumulation of GHGs such as (CO₂), methane (CH₄), nitrous oxide (N₂O), water vapors (H₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆) (Fig. 1) (IPCC 2013). As per the estimates atmospheric GHGs concentration has increased; such as CO₂ from 280 to 395 ppm, CH₄ from 715 to 1882 ppb and N₂O concentration from 227 to 323 ppb since 1750–2012 (IPCC 2013). It is reported that GHGs are now at their highest levels in the history of earth, with continuous increment and even if emissions are stopped immediately, climate change will still continue for years to come.

It is now projected that changes in temperature to extremes over different areas of earth are likely to occur earlier than was expected (Li et al. 2018). The average global surface temperature has increased by 0.74 °C since the late 19th century and is expected to increase by 1.4–5.8 °C by 2100 with significant regional variations (IPCC 2014; Harris et al. 2017). It is well known that the most important GHG is CO₂ which currently constitutes 76% of the total global warming impact. CO₂ production is increasing by most of the countries of the world and some countries with major contribution (%) in total CO₂ emission are depicted in Fig. 2. Although global CO₂ level is increasing but Bhutan is the only country with negative carbon value due to highest percentage of forest cover region (Climate Council 2017). Fossil fuel consumption is the main reason of carbon emission. It was estimated that in 2015 fossil fuel consumption accounted for 82% of total primary energy supply (Boden et al. 2017). Global carbon emissions are increasing due to coal burning (42%), liquid fuels (primarily oil) (33%), combustion of natural gas (19%), cement production and gas flaring (6%) (Boden and Andres 2016). It is reported that annual CO₂ emission due to fossil fuel combustion have intensely increased from nearly zero to over 33 Gt in between 1870 and 2014 (Fig. 3) (Boden et al. 2017). Rapid deforestation and land-use change have large impact on climate change as well (Ramankutty and Foley 1999; Scott et al. 2018). Destruction of wetlands, especially peatlands, mining and deforestation add significantly to the increased release of GHGs because these are carbon stores on earth (Bergkamp and Orlando 1999).

Climate change is causing conditions such as unusually warmer weather, melting glaciers, polar warming, coral-reef bleaching, heavy precipitation events, longer droughts and dry periods, a rise in sea level, changes in plant and animal distribution, increased environmental degradation and natural disasters (Loehman 2010; Kraaijenbrink et al. 2017). It is reported that Arctic’s ice has shrunk continuously since 1979, with 1.07 million km² of ice loss every
decade (Vaughan et al. 2013). Global mean sea level has risen by 12–22 cm in the last century and is predicted to rise further by 24–30 cm by 2065 and 40–63 cm by 2100 shrinking the land area (IPCC 2007) (Fig. 4). Global warming has resulted in warming of oceans leading to oceanic thermal expansion, further worsening the scenario and attenuating the availability of lands (Cazenave and Llovel 2010; Khan 2018). Global warming is also responsible for decreasing permafrost region resulting in decrease of about 20–35% and 30–50% area of permafrost region by 2050 and 2080 respectively, thereby releasing dangerous pathogenic bacteria and viruses which are buried in resting form (Wright 2017).

Climate change affects soil microbe–microbe and plant microbe interactions directly and indirectly and also causes reduction in soil microbial diversity (Bradford et al. 2008; Classen et al. 2015). Climate change is also accelerating the release of dissolved organic matter (DOM) and occurrence of pathogens on the globe which has increased exposure of infectious diseases in humans as well as wildlife and even spread of phytopathogens (Williamson et al. 2017). Wu et al. (2016) reported that climate change has impact on infectious diseases of humans by affecting the pathogens, vectors, hosts and their habitats. Climate change and extreme weather affect the spreading and intensity of major pathogens (Epstein 2001; Ostfeld and Brunner 2015).

Rising global temperatures are likely to increase the rate of soil organic matter (SOM) decomposition resulting in substantial CO₂ release subsequently resulting in loss of fertility of soil (Hopkins et al. 2012; Karmakar et al. 2016) and has the potential to accelerate climate change by up to 40% (Cox et al. 2000). Changes in climatic factors affect agricultural productivity and food security through direct and indirect actions (Tripathi et al. 2016) and the details have been discussed in the subsequent section.

In respect to severity of climate change Ban Ki-Moon, the UN Secretary-General stated that “We don’t have a Plan B, because there is no Planet B” in the UN’s 22nd conference in 2016, on climate change in Marrakesh, Morocco (Ki Moon 2016). Thus it can be said that in relation to adverse impact of anthropogenic activities, global warming and climate change are right on top and need to be tackled very quickly to restore the balance and biological alternatives/solutions can play very important role in combating climate change.

**Land degradation and agricultural constraints**

Land degradation is a problem confined not only to the compromised quality of soil but also linked to the diminution of the entire ecosystem along with the associated biodiversity, ecological cycles, ecosystem provisions like carbon sequestration, even affecting food prices, and forced migrations, affecting all life forms (Lal 2004; ELD-Initiative 2013). Land degradation has been categorized as a global issue by the UN Convention to Combat Desertification (UNCCD) resulting in alarming consequences on the health and productivity of soil resources (UNCCD 2002). According to estimates of Global Assessment of Land Degradation and Improvement (GLADA) a quarter of land area is declared to be degraded (Lal et al. 2012), with the economic loss of about US$ 230 billion annually (Nkonya et al. 2016). Of the total, 25% of land area is highly degraded, 8% moderately or slightly degraded, 36% stable and 10% improving (FAO-State of the World’s Land and Water Resources for Food and Agriculture (SOLAW) 2011). Hamdy and Aly (2014) stated that globally land degradation is directly influencing the lives of 1.5 billion people; annually there is a loss of 15 billion tons of fertile soils, whereas Global Soil Partnership (led by FAO) reports that 75 billion tonnes (Pg) of soil from arable land are degraded every year with financial loss of about US $400 billion (FAO-Global Soil Partnership 2017). There are several such reports available from time to time addressing the menace of land degradation, suggesting
causes and remedies but still the estimates are spurious and improvement is not taking place as well.

The vulnerability is also faced by agro-ecosystems where croplands alone contribute to 20% of the total world's degraded lands corresponding to the income loss of about US$ 10.8 billion (http://www.un.org/en/events/desertification_decade/whynow.shtml). The pitfalls of demographic pressures and un-sustainable agricultural practices have curtailed the productivity of agro-ecosystems. Low-income countries show higher percentage of marginal lands (about 20%) in comparison to high-income countries (19%) and middle-income countries (18%) (Fischer et al. 2010).

Climatic variability is playing a major role and is directly linked to land degradation and in reducing the productivity and fertility of agricultural lands (Tewari et al. 2016; FAO 2017). Climate change has been challenging various terrestrial ecosystems reducing the vegetation density, negatively affecting the soil microbial biomass, which is an important component of agro-ecosystems and thereby leading to desertification of lands because of high temperatures, scarce rainfall and accompanied soil and water erosion (Lal 2012). According to the report of FAO (2016) due to warmer climate, major agricultural crops (particularly the Rabi crops such as wheat) have experienced significant yield reductions globally. According to the IPCC for each degree rise in temperature, grain yields decline by about 5% (FAO 2016). The present heat wave and abnormal temperature rise in Europe has devastated crops, and has shown worst harvests ever since the end of Second World War. European countries including Hungary, Bulgaria and Romania where once major exporters are now importing food. Ukraine formerly known as breadbasket of the erstwhile Soviet Union, showed a 75% decrease of wheat production in 2018 as compared to average. Also due to irregular precipitation patterns and increased global temperature, severe weather events such as drought and floods have been a recurrent phenomenon further exacerbating wind or soil erosion (UNCCD Press Release 2015; FAO-IPCC 2017).

Drought is another menace which is engulfing more and more areas of the globe. Climate change has resulted in frequent cycles of drought and floods, and caused long periods of water scarcity resulting in desertification. Over the last 40 years there has been notable increase in droughts throughout the globe, particularly in tropics and sub-tropics (http://climaticca.org.uk/desertification-land-degradation-climate). Ever since the beginning of Anthropocene era, the world is facing water stress and environmental challenges mainly attributed to anthropogenic activities. The most obvious impact of drought is on the uptake of nutrients, as water is the transporting medium for nutrients in plants; increase in soil temperature leading to loss of beneficial microbial communities; drought also affects SOM decomposition causing increased carbon dioxide emission and also influences increased release of nitrate as its absorption by plants is reduced due to lack of moisture. These negative impacts cause long term soil infertility, due to imbalanced C, N contents and microbial diversity (Geng et al. 2015). Drought also causes damage to habitats through biodiversity loss, wildfires and soil erosion. African countries including Djibouti, Eritrea, Ethiopia, and Somalia have been majorly affected by droughts since last 12 years, Australia suffered multi-droughts between 2002 and 2010 and currently (in 2018) is facing second most severe autumn drought with reduced rainfall of 56.54 mm in comparison to average autumn’s rainfall of 102.3 mm (https://www.skymetweather.com/content/global-news/australia-undergoes-second-most-severe-autumn-drought-in-a-century/). The 2010 drought of Russia was the worst in the past 38 years of its history; US great grain belt drought of 2012 was responsible for increasing food prices by 3–4% (http://www.fao.org/docrep/017/aq191e/aq191e.pdf) and the 2014 Spanish drought was reported by country’s meteorological agency, Aemet, as the longest and one of the most intense in the span of last 150 years (https://www.thelocal.es/20140519/mega-drought-threatens-spain). The recent heat wave in Europe has increased the temperature above 40 °C and is also causing drought and wildfires across the continent. The emerging scenario of groundwater loss in India is also alarming, resulting in desertification. According to NASA report, Northern India is showing the highest groundwater declination in comparison to anywhere across the globe. NASA reported 108 cubic kilometers loss of groundwater in Haryana, Punjab, Rajasthan, and Delhi between 2002 and 2008 and the future consequences predict huge shortage of water leading to severe drought in these areas (http://www.wri.org/blog/2015/06/global-tour-7-recent-droughts). Even the major lakes and wetlands are stressed by drought due to increased withdrawals and other anthropogenic disturbances. For example, the area of Lake Urmia (second largest saltwater lake) has decreased by 80% since past 40 years, and major reduction has occurred between 2009 and 2015, major cause being construction of around 20 man-made dams around the lake to divert the flow to agricultural lands. As a result of this major desiccation the surrounding land has become degraded due to saline storms from the hypersaline lakebeds (https://eos.org/editors-vox/anthropogenic-drought-how-humans-affect-the-global-ecosystem). Similar scenario has also emerged in central Asia with the drying of Aral Sea which has shrunk to 10% of the former size. Soviet Union’s agricultural policies in the 1950s initiated the deterioration of Aral Sea (https://www.bbc.com/news/business-44159122). The menace of drought and desertification each year leads to the land loss of 12 million hectares (http://www.unccd.int/Lists/SiteDocumentLibrary/WDCD/DLDD%20Facts.pdf). For the given rise of temperature by 3–4 °C, the drought incident risk will increase from 10 to
40% in the coming years (Stern 2006). Drought has also negatively influenced the agricultural lands reducing the crop production. According to the report of FAO (2017), between 2005 and 2014 there has been approximately USD 93 billion loss in crop and livestock production in developing countries and agricultural sector suffered 23% of the total loss due to droughts. The frequency and duration of drought affects microbial community due to interrupted nutrient cycles (Santos-Medellín et al. 2017). Drought leads to impaired availability of water to plants resulting in various physiological impacts and complete destruction of the crops (Mayak et al. 2004).

Soil salinization is also a major reason of land degradation influencing most of the countries, with an approximate area of 1 billion ha (FAO 2015). Salinization of lands is interconnected with drought (Tewari and Arora 2013). The major causes of land salinization have been the use of improper irrigation methods and agricultural practices. Irrigation with low quality of water leads to accumulation of salts in soils, accompanying this, poor drainage worsens the scenario. Figure 5 highlights the influence of humans on increasing salinity correlated with CO2 emission, showing that with the increase in population, salinity and CO2 emission have enhanced simultaneously. The positive correlation coefficient (r) of 0.928 for population and salinity and of 0.937 for population and CO2 emission shows the dependency of the two on increase in human numbers on earth. Also the positive correlation of 0.9996 between CO2 and salinity depicts that salinity has even been influenced by carbon dioxide emission indirectly through various events caused by its effect. The injudicious use of chemical pesticides and fertilizers is also responsible for increasing soil salinity. Since 1945, about 17% of agricultural lands have lost fertility due to salinization because of the use of pesticides (Mishra et al. 2018). The stability of pesticides like parathion has been reported to increase in saline soils rendering them non-fertile (Reddy and Sethunathan 1985). Salinization has affected agricultural lands influencing the plant productivity and food security. The agricultural land degraded by salinity each year accounts for about 10 million hectares (Pimentel et al. 2004). About 20% of irrigated lands are under the influence of salinity which is responsible for producing one-third of world’s food (Machado and Serralheiro 2017). Salinity highly depresses the growth and yield of crops especially of vegetables which show very less tolerance to salt stress (Tewari and Arora 2014a, b; Ahmad et al. 2016). Saline soils are characterized by low moisture holding capacity, high electrical conductivity (EC) (4 dS/m or above), nutrient imbalance and the land becomes more vulnerable to flood, drought and soil erosion (Mishra et al. 2018). Salinity leads to Na+, Cl− toxicity, osmotic imbalance, ethylene stress, plasmolysis, nutrient deficiency, reduced photosynthetic rate, partial closure of stomata and generation of reactive oxygen species (ROS) in plants (Drew et al. 1999; Mishra et al. 2018). Salt toxicity also hampers the abundance, diversity, functioning and properties of beneficial soil microbes. If the situation continues at the present rate more than 50% agricultural land will become saline by 2050 (Bartels et al. 2005). Figure 6 shows the distribution of salt-affected lands (in million hectares) on globe.

Floods harm the quality of lands and disturb the vegetation and productivity of agro-ecosystems. Floods have been more recurrent phenomenon ever since 1950s correlating with the impact of climate change (Oh et al. 2014). Flooding causes major damage to fertile land due to severe erosion, denudation or landslides in hilly areas, accumulation of sediments, loss of plant nutrients, biochemical changes due to stagnant water, water logging, pollution

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**Fig. 5** Showing increment in salinity stress and CO2 emission rate in correspondence to increase in population through years. Data source: Munns and Tester (2008); Yan et al. (2008); FAO (2008); UNPD 2017; https://www.statista.com/chartoftheday/ (2018)

| Year | Population increase | Salinity | CO2 Emission rate |
|------|---------------------|----------|-------------------|
| 1980 |                     |          |                   |
| 1990 |                     |          |                   |
| 2000 |                     |          |                   |
| 2010 |                     |          |                   |
| 2020 |                     |          |                   |
| 2030 |                     |          |                   |
| 2040 |                     |          |                   |
| 2050 |                     |          |                   |
| 2060 |                     |          |                   |

Correlation coefficient (r):
- Population and Salinity $r = 0.928$
- Population and CO2 emission rate $r = 0.937$
- CO2 emission and salinity $r = 0.9996$
with harmful chemicals present in water etc. In plants, hypoxia due to water-logging causes poor root growth thereby leading to reduced water and nutrient absorption and stomatal conductance leading to wilting and productivity loss (Banga et al. 1995; Tewari and Arora 2016). As per FAO (2017), 37% cumulative production losses in crops and livestock production occur due to floods translating to about USD 34 billion. Cramer et al. (2011) mentioned that globally about 13% of world area is jeopardized by flooding and submergence.

Figure 7 depicts the recent occurrence of different disasters (flood, drought, storms, and extreme temperatures) around the globe.

Heavy metal pollution of land through various anthropogenic resources as mentioned earlier (in “Pollution” section) is also a reason for degradation of fertile land.

Ever since the onset of green revolution, prodigious concentration of agrochemicals including pesticides, fertilizers have been tracked in various ecosystems. The acute toxicifying effect started when the chemicals being used injudiciously during the era of green revolution started polluting majority of agro-ecosystems (Pingali 2012). These chemicals, particularly the pesticides remain in the soil for long because of their poor solubility, toxic nature, complex association with organic soil sediments, low degradability and deleterious impact on the soil microorganisms (Hunting et al. 2016). These agrochemicals influence the non-targeted species, cause pollution and incidence of various diseases in plants, animals and humans (Taylor et al. 2003; Arora et al. 2010). Being recalcitrant in nature pesticides accumulate in the food chain and cause great harm. Since 1940s, the concept of pesticides became popular with an increase of about 11% per year intensifying to more than 5 million tons in 2000 from 0.2 million tons in 1950s (FAO 2017; Carvalho 2017). But over the years their toxicity, fate in environment and influence on other biota were reported leading to the ban of many pesticides including DDT (Griswold 2012). Intensive use of harmful pesticides in the past has resulted in infertile soils due to loss of useful soil micro-fauna (Bezchlebová et al. 2007; Mishra et al. 2015). Boldt and Jacobsen (1998) reported that herbicide metsulfuron methyl was reported to be toxic to beneficial soil microorganisms even at very low concentration. Panda and Sahu (2004) concluded the negative impact of butachlor, a herbicide on earthworms. Insecticides have shown greater influence on soil biota through changing the microbial composition, affecting the earthworm reproduction cycle and lowering collembolans population (Endlweber et al. 2005; FAO 2015). The application
of agrochemicals has also altered the soil biological and physical properties and contaminates the soil with harmful chemicals (EEA 2013). Some organochlorine pesticides also inhibit biological nitrogen fixation. Pesticides have been found to be interfering with the flavonoid signaling in leguminous plants which are important in establishing symbiotic relationship by attracting rhizobia to the root systems (Potaera 2007). Pesticides also reduce bacterium’s respiration rate and nitrogenase activity (Mrkovaaki et al. 2001; Gulhane et al. 2015). In parallel to the application of chemical antagonists, chemical fertilizers were also excessively used from 19th century (Gilland 2015). To enhance the nitrogen (N), phosphorous (P), potassium (K) content of soil, bridging the gap between increasing population and food production, synthetic fertilizers have been applied and still are being used indiscriminately in agricultural fields. In fact several countries have subsidized fertilizers so as to make them cheaply available to the farmers and feed the ever-increasing human population. With short span benefits, these agrochemicals initially support excessive cultivation but later lead to soil salinization, acidification, desertification and biological imbalance. Agrochemicals have also been a prominent source of sulfur (S), nitrogen oxides and other trace element emissions (FAO 2015). Exceeding content of N, P in soils due to indiscriminate use of fertilizers are often weathered by soil, wind erosion and floods reaching other ecosystems like aquatic bodies leading to eutrophication and loss of water bodies. Bouwman et al. (2005) calculated that 16% of the N input is lost due to weathering and erosion thereby affecting associated environments. Ammonium based fertilizers lead to acidification of soils and are a major threat in several countries (FAO 2015). In spite of the reported drawbacks, agrochemicals are still heading the agro-markets throughout the globe. Application of urea as nitrogen based fertilizer has increased to almost 100 folds in last four decades with doubling evidenced in past decade (Gilbert et al. 2006; Azizullah et al. 2011). The ever increasing demand for food is pressurizing intensive cultivation, exploiting agro-ecosystems and reducing the fertility of lands. Over-cultivation has been responsible for degradation of 30% of global land area with the loss rate of 10 million hectares per year. Waggoner and Ausubel (2001) projected that the continued intensified production would lead to loss of 230 million hectares of global crop-land by 2050 (an area thrice the size of France). Increasing disposal of wastes on lands from factories, farms, hospitals, offices, mines, nuclear power plants etc. are accelerating the content of toxicants and non-degradable moieties on land. Before 20th century the wastes added to the lands were mostly natural and degradable. But with the introduction of non-degradable and toxic wastes the land degradation increased to unprecedented and unforeseen levels. About 13 tons of hazardous wastes are produced every second throughout the globe. In just one generation there is an increment by about 40,000% of man-made chemicals and a great part of these eventually goes into land and water bodies degrading them to a very dismal condition (http://www.theworldcounts.com/counters/waste_pollution_facts/hazardous_waste_statistics).

Apart from the aforementioned abiotic stresses, biotic stresses have also played a major role in impeding the quality of land, making them unfit for cultivation, reducing their availability for the future use. The presence of pests has always been a hassling issue impeding the agricultural growth rate and quality of soil (Singh and Arora 2016; Mishra and Arora 2017). FAO (2015) reported 20–40% annual reduction of the global crop yield due to pests and plant diseases. Globally pre-harvest pests are responsible for an average of 35% potential crop yield loss (Oerke 2006), along with high food chain losses (IWMI 2007). The synergism of biotic and abiotic stresses amplifies the detrimental responses of pests and phytopathogenic microbes (Jedmowski et al. 2015; Lamichhane and Venturi 2015). Drought stress is known to enhance the infection risk of phytopathogens in crop plants (Suleman et al. 2001; Goudarzi et al. 2011). Climate change also has noticeable impact on distribution of phytopathogens. The changing climatic conditions in European countries have drastically increased the population of insects which were once not reported in these regions, mainly because of increase in global temperature. Pests have started shifting towards north and south poles over the last fifty years in lineation with the climate change. On an average the recorded rate of 2.7 km per year, since 1960, has been observed for crop pests moving towards poles and in particular fungi and oomycetes show worrying movement rate of 7 and 6 km per year respectively (Bebber et al. 2013). A weather sensitive beetle Denroctonus ponderosae, which was earlier the native of mountain pines has now marched northwards, destroying pine forest in US Pacific north-west. The other trans-boundary pests include cottony cushion scale (Iceryapurchasi) found to be shifting northwards (Watson and Malumphy 2004); Western corn rootworm Diabrotica virgifera from Europe has been extending eastwards and northwards (Baker et al. 2003); in addition impact of Ralstonia solanacearum, causative agent of brown rot has become much serious with global warming; Dickeya, genus including mainly pathogens which were primarily endemic to tropical and warm climate, may now cause diseases even in Europe (Laurila et al. 2008) (FAO 2008). Agro-ecosystems are thus facing multitude of stresses due to mal-practices, huge input of chemicals and climate change. This is also resulting in loss of useful microbes from the soil. Need is to replenish the soils and practice eco-friendly methods in agro-ecosystems apart from reducing the impact of global warming and dangerous pollutants.

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Habitat and biodiversity loss

The loss of biological diversity has become a complex and unceasing problem. This has resulted in reduction of biological heterogeneity which in turn results in an unprecedented decrease in terrestrial and marine species including flora and fauna affecting overall stability of the ecosystems (Constanza et al. 1997; Arora 2018b). Reports of World Wide Fund for Nature (WWF) (2014) suggest that 52% of global biodiversity has been lost since the year 1970–2010. Extinction of plant species is the major concern as they play a key role in maintaining a balance in the ecosystem and directly affect its functioning by providing habitats to numerous other organisms (Monteiro et al. 2018). Extinction, although, is a natural phenomenon but wide range of human activities inducing the decline of biological diversity cannot be denied (Bitencourt et al. 2016). Extinctions caused by humans have intensified since last 40,000 years (Dirzo and Raven 2003). If these trends continue, it is suggested that within 240 years the earth will probably face its sixth mass extinction (Barnosky et al. 2011). In fact some researchers suggest that the sixth mass extinction of species has already begun and it is purely attributed to anthropogenic activities. According to estimates, 43% of the global terrestrial surface has been facing disturbances and the natural vegetation is taken over by man-made habitats (Barnosky et al. 2012). Rates of extinction are expected to rise to double the order of magnitude in this century and with increase in climate change this may speed up even further (Pereira et al. 2010; Barnosky et al. 2012). The historical trends in biodiversity loss across the world are shown in Fig. 8. The factors that are known to increase pressures on biodiversity are loss of habitat and its fragmentation, climate change, overexploitation, environmental pollution, spread of diseases, invasive alien species and hunting/fishing (Baillie et al. 2010; Beumer and Martens 2014; Keziah and Devi 2017; Arora 2018b).

Habitat loss and fragmentation are the major threats to biodiversity and both are interdependent on each other (Brooks et al. 2002; Hanski 2011). The increasing demand for resources such as land use for agricultural purposes and expansion in cattle raising, mining activities and building infrastructures due to population explosion have led to the metamorphosis of natural habitats, resulting in their degradation and have posed serious threats to the habitats of plants and animals (de Sherbinin et al. 2007; Hanski 2011). This drastic change in land cover area can lead to a loss of up to 40% of species diversity in most biologically diverse areas worldwide (Pimm and Raven 2000). However, apart from this, other anthropogenic activities are also playing key role in diminishing the biodiversity on earth.

Forests/natural habitats around the globe are facing issues such as climate change, pollutants, faulty agricultural practices, causing loss of biodiversity at an alarming rate. Temperate forests in South America, one of the 35 global hotspots have been reduced by 70% (Myers et al. 2000; Echeverrï¿½oa et al. 2006). Similarly, tropical forests, another rich source of biodiversity have been lost up to 10% in past 25 years with a depletion rate of 0.8% per year as a result of man-made activities (Arora 2018b). Recently, Islam and Bhuiyan (2018) reported how the largest mangrove delta of the world, the Sunderbans mangrove forests, are shrinking and degrading resulting in huge impact on the depletion of the biodiversity of the region.

Approximately 72% of the surface of the earth is covered by oceans and this constitutes greater than 95% of the total biosphere (UNEP–United Nations Environment Programme 2017). According to Organization for Economic and Co-operative Development (OECD) (2016), nearly 2.6 billion people are dependent on oceans for protein uptake which accounts for 16% of total global animal protein. Vegetated ocean habitats and mangroves are known as “Blue Carbon” sinks which trap 25% of the CO₂ generated from fossil fuels and keep coastal communities safe from floods.
and storms [World Bank-UNDESA (United Nations Department of Economic and Social Affairs 2017)]. However, due to anthropogenic activities the oceans around the globe have been impacted (Swan et al. 2016). This has resulted in the impairment in the capacity of oceans to provide ecosystem services, and the cushion to the environment against the anthropogenic activities is now in danger (Halpern et al. 2015; Nguyen et al. 2018). In fact oceans and poles are now amongst the most fragile ecosystems on the earth.

Global climate change is directly hampering the biodiversity and causing degradation of habitats (Kappelle et al. 1999; Pereira et al. 2012). Environmental conditions are changing in a drastic and non-sequential manner that can have serious consequences on the ecosystems around the globe (van Nes et al. 2016). It is now estimated that 34% of the total biodiversity loss is due to global warming. Global warming and climate change as pointed in earlier section as well, create a shift in species distribution and have hiked the risk of extinctions of species particularly in the habitats which are shrinking due to climate change (Thomas et al. 2004; Parry et al. 2007). If reports are to be believed, owing to global warming it is estimated that 15–37% terrestrial species will face extinction by 2050 (Tang et al. 2018). Several meta-analysis studies reveal that there is an alteration in the life events of species due to rising temperatures (Miller-Rushing and Primack 2008; Forrest et al. 2010). Marine species are at even higher risk due to rising temperatures and events of heat waves which are increasing by the day (both on land and in oceans). This is because marine life is acclimatized for fewer variations to temperature in comparison to land organisms (Costello and Chaudhary 2017). Investigations on tropical streams show that warmer temperature affects the communities of macroalgae (Bojorge-Garcia et al. 2010), cause shifts in fish physiology and diversity (Rolla et al. 2009), and as a result, causes a destabilization in food web of the aquatic systems (Motta and Uieda 2005). Deoxygenation of ocean is a major issue due to climate change. Oxygen loss by over 2% have been recorded in the open ocean at global level in last 50–100 years and is projected to continue to greater extent in next 100 years (Levin 2018). Among the tropical oceans, a decline of up to 20% of marine phytoplanktons in Indian Ocean has been observed since past 60 years due to the effect of warming. This elevated temperature has also hampered marine productivity (Roxy et al. 2015). According to currently classified IUCN Red list, there are 1206 marine species which are either critically endangered, or vulnerable (Webb and Mindel 2015). This report depicts the situation of only a fraction of marine taxa and in near future the condition will become worse as predicted by report of Cheung et al. (2009) which states that climate change will threaten additional taxa and hence will result in 60% deviation in marine biodiversity across the globe. Climate change also has other adverse impact as emissions from GHGs cause coral bleaching (Hoegh-Gulberg and Bruno 2010). Coral reefs have been lost by up to 38% since 1980 across the globe (Hume et al. 2016). Moreover, global warming is expected to cause drying of lakes especially in Africa leading to their degradation and loss of biodiversity (Campbell et al. 2009).

Pollution of air and water also affect the balance of the ecosystem and largely affect the biodiversity of the land. Acidification of lakes and soils, eutrophication of waters and bioaccumulation of metals/heavy metals in food web and plethora of other problems occur due to pollution (Lovett et al. 2009). Pollutants such as polyaromatic hydrocarbon (PAHs) and PCBs from effluent discharge and oil spills which when released in water bodies affect biology of that system. By-products generated by human interventions like particulate matter, heat and chemicals have further amplified the chances of extinction of species in water bodies (Alruman et al. 2016; UNEP 2017).

Microbial diversity is also affected by environmental pollution. Microorganisms are the major components in terms of biomass, genetic diversity and metabolic roles they play in the ecosystems. Hence the stability of ecosystems is directly related to the population and diversity of microbes (Panizzon et al. 2015). Microbes are also largely responsible for decomposition of organics, xenobiotics and recalcitrants, and formation of soil aggregates (Kennedy 1999). There are approximately 50 million bacterial cells that reside in a gram of soil and in case of oceans around 90% of its biomass is composed of microbes (Arora 2018b). It has been reported that as a result of soil pollution, microbial diversity reduced drastically (Gans et al. 2005). Genomic studies provide clear evidence in the shift of synergy and functioning of microbial biomass (Degrune et al. 2017). Reduction in microbial diversity can easily affect the sustainability of the ecosystem because of the shear role these organisms play. However, it is not easy to determine the microbial diversity of any ecosystem. Recent studies are though clearly suggesting the impact of pollutants such as pesticides on microbial diversity. In a recent study Arora et al. (2018) reported decline in nodulation in legume crops due to pollution and salinity. Moreover, excessive use of nitrogen rich chemical fertilizers have reported to cause acidification and degradation of SOM which results in deterioration of soil health making it unproductive (Ju et al. 2009; FAO and ITPS 2015). Therefore, urgent corrective measures are required to ensure the biodiversity conservation and habitat loss reduction to sustain the civilization.

**Sustainable solutions**

Aforementioned environment issues raised debates about the corrective measures that have to be taken so as to prevent further deterioration of environment. Though scientists and environmentalists have documented the magnitude and
significance of these environmental problems since decades, little success has been achieved so far in achieving the targets. Apart from this, sustainable solutions of environmental problems are more often overlooked and instead of this, technical approaches are used. Hence, for creating a sustainable environment a corrective plan must be implemented which encompasses biological solutions or greener approaches. This section discusses sustainable solutions, mainly biological approaches, to tackle the various problems caused by anthropogenic activities.

**Microbes as key players**

Microbes are ubiquitous and present in every part of biosphere. Microbes are very diverse in nature and their presence everywhere suggests the roles they can play in maintaining the ecosystems. Due to their flexible and adaptive genetic makeup and versatile metabolic capabilities microbes can be used for the solution of various environmental issues, particularly related to treatment of pollution, combating climate change and global warming, land reclamation, enhancing agricultural productivity, tackling industrial effluents, remediation of waste and pollution affected systems (Ahmad et al. 2011; Mishra et al. 2017; Akinsemolu 2018). Microorganisms, particularly bacteria and fungi can be employed to tackle the issues in simple and economical manner by minimal inputs and issues.

**Biodegradation and bioremediation**

Application of microbes can serve as a powerful tool in handling the problem of environmental pollution. Microbes can be wonderful cleaning agents and can degrade almost everything (Gupta et al. 2018). Biodegradation involves removal of pollutants generally at source by the help of biological means, mainly microorganisms (Abatenh et al. 2018). Microbial techniques are used as suitable alternatives to various traditional methods for degradation of waste materials (Blaszak et al. 2011). A diversity of microorganisms can be utilized for detoxification of xenobiotic organic compounds in a very sustainable manner. Khatoon et al. (2017) reported biodegradation as an important technique for removal of various polymeric pollutants through microbial applications. In bioremediation, microorganisms or other biological systems such as plants (phytoremediation) or plants plus rhizospheric microbes (rhizoremediation) are utilized for reclamation of already contaminated habitats by transformation of pollutants into less-hazardous or non-hazardous substances (Coelho et al. 2015). Bioremediation is a very promising, eco-friendly and effective technology which is applied to remove hazardous pollutants (pesticides, heavy metals, PAH, PCBs, halogenated organic solvents and radio nuclides) from the environment (Lal et al. 2010; Abhilash et al. 2016; Kotoky et al. 2018). On the basis of their application sites bioremediation is of two types in situ and ex situ. In ex situ method contaminated soil or water is excavated and transported to laboratory or industry for treatment. This method is a bit complicated and involves more capital input but is a swift process and can be used for recalcitrant and diverse range of contaminants under optimum conditions (Philp and Atlas 2005; Azubuike et al. 2016). In situ remediation of pollutants is done on the site. This is simpler, cheaper and convenient in comparison to ex situ method. In in situ technique native microbes (present at the contaminated sites) are used to cause remediation by utilization of sufficient amount of nutrients essential for their metabolism (Bhatnagar and Kumari 2013). Under suitable environmental conditions rate of bioremediation is increased by supporting microbial growth of autochthonous species (Verma and Jaiswal 2016).

Soil contaminated with pollutants is a major threat to human health and cause many environmental problems such as pollution of ground water and reduction in fertility (Fredua 2014; Panagos et al. 2018). Microbes are used as sustainable tools for the removal of pollutants from agriculture lands which helps in reclamation of contaminated soils (Verma et al. 2017). Application of microbial bioremediation works as low-cost technology for clean-up of pollutant contaminated sites. Pollution of ocean and coastal areas is of much concern around the globe due to increase in intensity of contaminants. Sakthipriya et al. (2015) and Parthipan et al. (2017) used biosurfactant producing microorganisms for bioremediation of crude oil and petroleum contaminants very efficiently. Similarly Tanzadeh and Ghasemi (2016) reported the application of microorganisms for bioremediation of oil spills in sea waters and coastline.

Microbes play very promising role in environmental sustainability by performing wastewater treatment and recycling of thermal, agricultural and industrial wastes (Sharma et al. 2013a; Cydzik-Kwiatkowska and Zielińska 2016). Discharge of industrial effluents is a major problem. The effluents and the contaminated sites can be remediated by application of microbes such as Bacillus, Pseudomonas, Flavobacterium, Alcaligenes, Acinetobacter and Zoogloea sp. (Kumar et al. 2011; Maulin 2017). In this context Mandal et al. (2012) reported large scale bioremediation of petroleum hydrocarbon contaminated waste at Indian oil refineries by application of indigenous microbial consortium on field and successfully bioremediated 48,914 tons of different types of oily waste. Gonzalez-Martinez et al. (2018) reported the full-scale biological wastewater treatment systems in the Polar Arctic Circle region in Finland by using archaea, bacteria and fungi. Industrial effluents contain various hazardous components and microbial treatment cause detoxification of those components (Shaker-Koohi 2014).
Microbes have strong ability to cause the remediation of chemical pesticides. Hussain et al. (2016) reviewed the degradation of various neurotoxic pesticides (neonicotinoid) from water and soil systems by application of various bacteria such as Bacillus, Pseudomonas, Burkholderia, Mycobacterium etc. In this regard Akoijam and Singh (2015) reported the application of Bacillus aerophilus for degradation of imidacloprid. Yin et al. (2012) reported the biodegradation of cypermethrin by a bacterium Rhodopseudomonas palustris GJ-22 isolated from activated sludge. In another example scientists reported the degradation of chloropyrifos from Kashmir valley, India, due to presence of naturally occurring Escherichia coli (EC1) and Pseudomonas fluorescens (PF1) (Altaf 2018). According to Kumar et al. (2018a) various microbial strains such as Aspergillus, Pseudomonas, Chlorella, and Arthrobacter, cause the degradation of organophosphate pesticides. Phenolic compounds such as bisphenol compounds, phenols, alkyl phenols and natural steroid hormones produced from various industries (pesticides, pharmaceuticals, preservatives, fungicides) are also very dangerous for environmental health and negatively affect all organisms on earth (Zhao et al. 2018). Microbes can be used as very effective tools to degrade these phenolic contaminants (Gu et al. 2016). Mendoza et al. (2004) reported the application of fungus Fusarium flocciferum for the degradation of aromatic compounds, namely, gallic, protocatechuic, vanillic, syringic, caffeic, and ferulic acids and syringaldehyde from agro-industrial wastes. Similarly Liu et al. (2016) and Mohanty and Jena (2017) also reported the biodegradation of phenol by bacterial strain Acinetobacter calcoaceticus and a novel bacterium Pseudomonas sp. (NBM11) respectively. Recently Singh et al. (2016) reported the application of immobilized Pseudomonas putida and Pseudomonas stutzeri for very effective and simultaneous biodegradation of phenol and cyanide present in coke-oven effluent. Metal contamination from soil can also be removed by soil microbial activity mainly by geo-active action (Mishra et al. 2017). According to Ayangbenro and Babalola (2017) application of microbial bio-sorbents is used as a new strategy for removal of heavy metal pollution. In this context Kim et al. (2015) designed a batch system using zeolite-immobilized Desulfovibrio desulfuricans for removal of various heavy metals from contaminated seawater.

Rhizoremediation is a process in which clean-up of the hazardous pollutants and wastes is done by rhizosphere microflora of plants (Oberai and Khanna 2018). This technique can be successfully used for reclamation of contaminated sites by selecting suitable plant cultivars along with rhizobacteria (Kamaludeen and Ramasamy 2008; Kotoky et al. 2018). Rhizoremediation is a low cost, rapid and efficient technique to remediate contaminated sites. According to Shahzad et al. (2016) this technique is very useful for remediation of all types of contaminated sites including oily sludge contaminated soils by enhancing the oxygen and nutrient availability in soil and improves the soil texture also.

Some successful stories about bioremediation of major contaminated sites are reported from around the globe (Table 1). The global market for bioremediation of major contaminated sites is reported from around the globe (Table 1). The global market for bioremediation technology and services was valued at US$ 32.2 billion and is estimated to reach US$ 65.7 billion by 2025 at a CAGR of 8.3% from 2017 to 2025.

### Combating climate change

Reduction in change of climate and impacts of global warming is urgently required for present as well as future. Various types of measures are taken for combating climate change and global warming and microbes have great potential to do the task (Willey et al. 2009; Abatenh et al. 2018). Various types of microbes are known for their application in controlling global warming. Methylotrophs such as Methylocabillus and Methylokonos infernorum found in geothermal areas in acidic and hot environment and anaerobic aquatic conditions (benthic zones of lakes and sea) help in reduction of GHGs particularly CH$_4$ by using them as growth substrate (Chistoserdova et al. 2009). Methylotrophs (methanotrophs) present in soil and water bodies consume large amount of methane (800–1000 kg CH$_4$ per ha per year) from environment which affect the global methane budget and reduce the impact of global warming and climate change (Mohanty et al. 2006; Pandey et al. 2015). Some microbes are also able to convert CO$_2$ into insoluble calcium carbonate or calcite that can reduce their load in atmosphere (Mitchell et al. 2010). Anbu et al. (2016) reported that microbial strains of Sporosarcina pasteurii and Bacillus megaterium show great ability of calcite formation by using CO$_2$.

Cyanobacteria as phytoplanktons have important role in reduction of global warming by consuming CO$_2$. It is reported that cyanobacteria are estimated to be responsible for 20–30% carbon sequestration through photosynthesis (Piscotta et al. 2010). Oceans are known as the largest carbon reservoir on earth and consume about one-third of all human carbon emissions. It is reported that about half of the carbon dioxide on earth is sequestered or fixed by cyanobacteria and other ocean microbes mainly through photosynthesis and can be converted into carbon-rich lipids which can be used for biofuel production (Case and Atsumi 2018; Pathak et al. 2018). Cyanobacteria can be used in photo-bioreactors as an important approach for mitigation of CO$_2$ through high fixation rate (Rangel-Yagui et al. 2004; Singh et al. 2016). Global warming can also be combated by the use of biofuels. Microorganisms such as Sulfolobus
solfataricus, Saccharomyces cerevisiae and Trichoderma reesei have been employed for production of biofuels from agricultural wastes (Gupta et al. 2014). Microbes also have role in water retention and control of soil erosion by enhancing the biomass and soil aggregation (Abhilash et al. 2016).

Being the major biomass and components of SOM these autochthonous microbes are the very important sinks of carbon on land. It is thus very crucial to maintain the diversity of soil and aquatic microorganisms.

Beneficial soil microorganisms can reduce the impact of climate change by enhancing the productivity of agro-ecosystems as well as by reclamation of waste and marginal lands by making them fertile (Tewari and Arora 2013). These microbes can increase the soil organic content of wastelands and infertile or stressed soils (Mishra et al. 2016). Climate smart agriculture using plant growth promoting microbes (PGPM) as biofertilizers and biopesticides can help in combating the impact of climate change. It is suggested by various researchers that applications of microbial inoculants in agricultural crop productions can be used as sustainable tools to overcome the negative effects of climate change as well as global warming (Dimkpa et al. 2009; Nie et al. 2015). Higher application of microbial inoculants in agriculture minimizes the chemical load which also reduces risk of global warming and climate change (Mishra et al. 2016). Reduction of waste and contaminated lands by application of microbial bioremediation and biodegradation can also help in combating the effect of climate change (Sinha et al. 2010).

### Table 1

| S. no. | Success stories at major contaminated sites | Microbes used | References |
|-------|---------------------------------------------|---------------|------------|
| 1.    | Removal of zinc (Zn) and sulphate in France | Consortium of sulfate reducing bacteria | Bruschi and Goulhen (2006) |
| 2.    | Clean-up of chlorinated solvents at the site New Hampshire, United Kingdom | Naturally occurring microbes with addition of biostimulants (mixture of yeast & lactose) | Schaffner (2004) |
| 3.    | Shore-line clean-up of Prince William Sound, Alaska, after the Exxon Valdez oil spill in U.S. | Oil degrading indigenous microorganisms | Boopathy (2000); Das and Chandran (2011) |
| 4.    | Clean-up of Deepwater Horizon oil spill in the Gulf of Mexico, U.S. | Oil degrading indigenous microorganisms | Atlas and Hazen (2011) |
| 5.    | Bioremediation of polycyclic aromatic hydrocarbon (PAH) polluted soil near Oviedo, Spain | Bacillus and Pseudomonas | Pelaez et al. (2013) |
| 6.    | Bioremediation treated over 160,000 tonnes of soil from a 1000 acre Bermite site from Los Angeles, California | Perchlorate reducing bacteria with glycerine-diammonium phosphate (DAP) | Evans et al. (2008) |
| 7.    | Remediation of oily sludge of Mathura oil refinery, India | Acinetobacter baumannii, Burkholderia cepacia and Pseudomonas | Mishra et al. (2001) |
| 8.    | Clean-up of mercury contaminated wastewater at Electrolysis Factories in Europe and technique known as BIOlogical MERCury Remediation (BIOMER) | Mercury resistant bacteria | Leonhäuser et al. (2013) |
| 9.    | Remediation of diesel contaminated soil at Lysimeter station Siebers of Austria | Microbial consortium (Pantoea sp. and Pseudomonas sp.) | Hussain (2016) |
| 10.   | Bioremediation of fuel oil contaminants in Florida | Commercial microbial inoculum and fertilizer | Jones and Greenfield (1991) |
| 11.   | Treatment of old zinc refining site at Bodelco, Netherlands | Sulphate reducing bacteria | Hockin and Gadd (2007) |
| 12.   | Clean-up of Amoco cadiz spill off the coast of France | Hydrocarbon degrading microbes | Atlas (1981) |
| 13.   | Clean-up of surface waters contaminated by the IXTOC I in the Bay of Campeche, Mexico | Hydrocarbon degrading microbes | Atlas (1981) |
| 14.   | Treatment of crude oil contaminated shoreline of Delaware Bay, US | Natural microbial inoculum from the site | Venosa et al. (1996) |
| 15.   | Application of biofiltration to treat gasses from soybean toasters in Hengelo, Netherland | Biofilm with peat | OECD (1994) |
| 16.   | Degradation of petroleum hydrocarbons in a polluted tropical stream in Lagos, Nigeria | Pseudomonas aeruginosa, Acinetobacter lwaffi and Corynebacterium sp. | Adebusoye et al. (2007) |
| 17.   | Treatment of azo dyes of wastewater discharged from textile and dye industries in Hon Kong | Acetobacter liquefaciens | Sharma (2010) |
| 18.   | Removal of hydrocarbons from oil refinery site in West Africa | Bacillus subtilis, Aspergillus sp. and Penicillium sp. | Nkeng et al. (2012) |
Role in sustainable agriculture

The fertility of soil is a parameter not only confined to availability of nutrients but also the microbial flora flourishing in the soil. Soil microbes maintain the fertility of agro-ecosystems and sustain the crop productivity by maintaining the ecological balance. But the problem is that due to heavy input of chemicals in agro-ecosystems several of these beneficial microbes are getting depleted or extinct from the soil. Apart from this there are several other drawbacks of using chemical fertilizers and poisonous pesticides which have already been discussed. Hence there is requirement to augment beneficial soil microorganisms into the affected as well as un-affected agro-ecosystems so as to increase the yields in eco-friendly manner.

The area around the plant root was first described by Hiltner as ‘rhizosphere’. The rhizosphere is a high activity zone with rich diversity of microbes which are mainly mutualistic with the host plant and help them in various ways (Hiltner 1904; Hartmann et al. 2008). Among the diversity of microbes in the rhizosphere, plant growth promoting rhizobacteria (PGPR) are the most efficient players in sustaining the productivity of agro-ecosystems. PGPR are significant colonizers of plant roots present in notable numbers in rhizosphere (Spaepen et al. 2008). The term PGPR was first defined by Kloepper and Schroth (1978) as organisms that on application on seeds could successfully colonize and positively promote the growth of plants. PGPR promote or protect the plant health by direct or indirect mechanisms. Through direct mechanisms PGPR promote growth of plants by providing nutrients such as N, P, zinc (Zn), iron (Fe); production of phytohormones, thus enhancing the growth and yields. Indirect mechanisms include protection from phytopathogens. Biofertilizers or biostimulants are the microorganisms which enhance the growth or crop yields by making nutrients or growth hormones or growth factors available to the plant (Vessey 2003). North America has the largest global market share in biofertilizer/biostimulants and is expected to grow further at a compound annual growth rate (CAGR) of 16.65% till 2022. Europe stands second with growth at CAGR of 14.9% till 2022, Asia-Pacific currently is third highest global shareholder (as per NOVONOUS estimates; Global Bio Fertilizer Market 2016–2020), Global market of different types of biofertilizer depicts 78.70% as nitrogen fixing, 14.6% as phosphate solubilizing and 6.7% as others (http://blog.agrivi.com/post/biofertilizers-an-innovative-tool-for-agriculture).

Microbial inoculants directly affect the soil fertility by increasing the SOM and thereby enhancing the yield of plants. Nitrogen fixing, phosphate and potash solubilizing microbes are the major biofertilizers used, where nitrogen fixing biofertilizers hold the largest global market and is expected to increase at a CAGR of 13.25% till 2020. Nitrogen (N) is a vital macronutrient required by the plants for their development and various metabolic processes. Thus, the unavailability of nitrogen limits the growth of plants and it is also one of the most important limiting factors for crops. The most efficient nitrogen-fixing bacteria are rhizobia which form symbiotic associations with leguminous plants. Rhizobiosis-legume symbiosis fixes approximately 40 million tons of nitrogen into agricultural systems every year (Herridge et al. 2008). The first nitrogen fixing biofertilizer ‘Nitratin’ was rhizobia based (Nobbe and Hiltner 1896).

As per present estimates, approximately 2000 tons of rhizobial inoculants worth US$ 50 million are produced every year which are sufficient to inoculate 20 million hectares of legumes (Ben Rebah et al. 2007). Apart from rhizobia, blue green algae (BGA), Azotobacter, Azospirillum, Frankia, are also commonly used as nitrogen fixing biofertilizers throughout the globe.

Phosphorous (P) is another essential element for the growth and development of plants. Its availability in soil is the prime determinant of fertility and productivity of agro-crops (Tak et al. 2012). Although the content of P in soil is 0.05% (w/w), only 0.1% of it is available to plants while the remaining is present in insoluble forms (Zhu et al. 2012). Through a number of transformations and chelation cascades some PGPM solubilize or chelate insoluble P making it available for plants (Babalola and Glick 2012). These groups of microbes are referred as phosphate solubilizing microorganisms (PSM) (Alori et al. 2017). P solubilizing biofertilizers hold the second largest global market share (after N biofertilizers) and their market is estimated to increase at a CAGR of 20.75% till 2020. PSM also are responsible for improving fertility and agricultural efficiency of saline and alkali soils avoiding the harmful effects of chemical fertilizers (Alori et al. 2017). Fungi including Rhizophagus (formerly Glomus) intraradices and Funnelliformis (formerly Glomus) mosseae have commercially been used as inoculants in Europe and US (Krüger et al. 2012); the market of phosphate mobilizing arbuscular mycorrhizal fungi (AMF) has been significantly rising throughout the globe (Vosátka et al. 2012). Recently the phosphate solubilizing abilities of actinomycetes is coming up because of their capability to survive under extreme conditions (e.g. drought or salinity) along with contribution to other plant growth promoting aspects (Hamdali et al. 2008; Sharma et al. 2013b).

Potassium (K) is the third most important mineral which is generally deficient for plants (after N and P). K is responsible for growth, metabolism and development of plants and their deficiency can cause impaired growth of roots, smaller seeds, reduced yields and higher susceptibility to diseases (Troufflard et al. 2010; Meena et al. 2014). With unfeasible and unsustainable aspect linked to the use of potash as K-fertilizer, the strategy is getting unpopular in the long run. Thus, switching to the use of eco-friendly and cheap K
bio-fertilizers, is the better option. The application of K-solubilizing biofertilizers can be very important for the sustainability of ecosystems because the quantity of it removed from soil by mining (to make fertilizers) is much higher and harmful for the environment (Meena et al. 2014). K-solubilizing bacteria are able to chelate K from insoluble forms. Examples of microbial genera showing K-solubilization include Bacillus, Arthrobacter, Enterobacter, Paenibacillus, Pseudomonas, Cladosporium, Aminobacter, Sphingomonas, Burkholderia, Acidothiobacillus, Aspergillus, Penicillium, Clostridium, Trichoderma and Serratia (Etesami et al. 2017; Bashir et al. 2017).

‘Hidden hunger’ due to deficiency of micronutrients has been another major issue faced by world today, which limits the physical, intellectual and social potential of individuals. Hidden hunger affects 2 billion people worldwide (http://www.fao.org/about/meetings/icn2/news-archive/news-detail/en/c/265240/). The stats of undernourished people are highest in sub-Saharan Africa and South Asia (http://www.downtoearth.org.in/news/hidden-hunger-a-silent-epidemic-46924). To combat the problem of hidden hunger, there is need to elevate the concentration of micronutrients in crops. Thus, biofortification of staple foods is an urgent need to meet the nutritional demands of the population. Changing atmospheric conditions especially the increase in CO2 level is leading to reduced micronutrients concentration in grains (Fernando et al. 2012). Thereby, the bioavailability of Zn and Fe can be increased by either application of fertilizers (bio/synthetic fertilizers) or by genetic breeding. PGP bacteria and cyanobacteria have been reported as efficient biofortifying agents increasing the content of micro-nutrients and proteins in staple crops such as rice and wheat (Rana et al. 2015). Mycorrhizal fungi and fertilizer seeds have also been used in biofortification of wheat (Nooria et al. 2014). PGPR are the best options for biofortification because they have shown sustainability and better results in comparison to the application of chemical fertilizers or the use of transgenic varieties.

Abiotic stress management  Microbes are successful tools in ameliorating abiotic stresses in agro-ecosystems. Microbes have been used to combat the stresses such as drought, temperature, pH, heavy metal and salinity and enhance the crop productivity in hostile conditions (Tewari and Arora 2016). PGPM have shown to be the preferable option in mitigating the negative impacts of the abiotic stresses through various tolerance mechanisms such as synthesis of osmoprotectants (K+, glycine, trehalose, proline, glutamate), exopolysaccharides (EPS), phytohormones (indole-3-acetic acid IAA, Gibberellic acids GA), siderophores, biosurfactants and enzymes such as ACC deaminase (Barriuso et al. 2008; Mishra and Arora 2017).

Drought stress. PGPM are known to help plants to survive under drought conditions. Many PGPM produce EPS which enhance water circulation in plants and also improve the quality of soil. EPS produced by PGPM aggregate soil particles trapping water molecules, hydrating soil and maintaining water retention capacity and nutrient uptake under drought conditions (Tewari and Arora 2014a, b; Mishra et al. 2018). PGPM also facilitate drought stress tolerance through production of cytokinins, antioxidants and ACC deaminase. Cytokinins are responsible for accumulation of abscisic acid (ABA) which further leads to closure of stomata to minimize foliar water loss (Figueredo et al. 2008; Ngumbi and Klopper 2014). Production of antioxidants by PGPM mitigates the damaging effect of ROS in plants. The antioxidant activity thus reduces the damage to cells, biomolecules and membranes (Grover et al. 2011). With the onset of drought stress, ethylene is produced in the plants. PGPM act against the synthesis of ethylene by production of enzyme ACC deaminase which acts as an ACC sink. The mechanism involves the conversion of ACC (the precursor of ethylene synthesis) to ammonia and α-ketobutyrate thereby, extruding ACC from roots to soil (Zahir et al. 2011; Saleem et al. 2018). The symbiosis between plants and AMF proves very beneficial in ameliorating drought stress and protecting the plant by increasing the antioxidant activity and regulating osmotic balance and root hydraulic properties, also maintaining the photosynthetic rate (Yooyongwech et al. 2016; Quiroga et al. 2017). The extension of hyphal network by AMF also serves as a stress alleviation strategy increasing the uptake of water and nutrients by plants (Evelin et al. 2009). At molecular levels the tolerance mechanism by PGPM involves altered gene expression such as up-regulation of marker drought-response genes (Gagné-Bourque et al. 2015) which further control various metabolic cascades through down or up-regulation of associated genes (Naylor and Coleman-Derr 2017). Apart from stress responses PGPM also are responsible for their marked functioning i.e. plant growth promotion. Even under stress conditions, PGPM show increased production of phytohormones like IAA and GA enhancing root and shoot growth (Glick 1995), nutrient recycling by phosphate, Zn solubilization, siderophore production, diazotrophy, (Kim et al. 2012), leading to overall improvement of plant growth (Timmusk et al. 2014; Gagné-Bourque et al. 2016).

Salinity stress  Osmotic stress due to hypertonic environment (resulting from accumulation of Na+ and Cl−) is the
immediate and most critical aspect of salinity which diminishes the soil quality and inhibits plants growth (Munns 2002). Plants are more sensitive to salinity as compared to microbes. Thus, increasing the tolerance of plants can be achieved by inoculation of salt tolerant microbes. Through the involvement of intricate mechanisms and adaptive signaling cascades salt tolerant PGPM establish mutualistic soil–plant-microbe relationship even under osmotic stress conditions (Mishra et al. 2017). The initial osmotic shock experienced by plants after salinization is mitigated by microbes through synthesis of osmolytes and phytohormone signaling (Chen et al. 2007). Osmoprotectants/osmolytes/compatible solutes are low molecular intra-cytoplasmic soluble sugar molecules synthesized by salt-tolerant microbes to counter osmotic stress (Sleator and Hill 2001). The other adaptive strategy by salt tolerant PGPM is the synthesis of polysaccharides to promote adherence to environmental surfaces and form a local hydrated environment isolating from desiccating surroundings (Awad et al. 2012; Mishra et al. 2018). EPS producing bacteria form a protective rhizosheath between the roots of plants and microbes, acting as a hot-spot of nutrient recycling, ion and water balancing (Sandhya et al. 2009; Bhargava et al. 2016). Under saline conditions, EPS producing bacterial inoculants also encounter Na⁺ toxicity by immobilizing the ions and stabilizing the soil ionic balance. EPS have also been reported in influencing the biological, physical and chemical properties of soil by forming stable aggregates with pore spaces trapping water and nutrients under salt stress conditions preventing excessive evapo-transpiration (Helliwell et al. 2015; Ilangumaran and Smith 2017). EPS producing fungi also are known to mitigate salinity stress by entangling and enmeshing soil particles in macro-aggregates (Bossuyt et al. 2001). Salinity stress in plants elevates the ethylene content retrograding the growth and development of plants (Ahmad et al. 2011; Mishra et al. 2018). To abate the detrimental influences of ethylene, microbes initiate the production of ACC deaminase (as mentioned in drought stress), sinking ethylene and in return providing nitrogen and energy to plants (Selvakumar et al. 2012; Egamberdieva and Lugtenberg 2014). ACC deaminase also helps the plants in uptake of nutrients like N, P, K, thereby maintaining the K⁺/Na⁺ ratio, a much desired condition in salt-stressed plants (Nadeem et al. 2009). Furthermore, salt tolerant microbes also mitigate the adversity of ROS by synthesis of antioxidants in a similar manner mentioned in drought stress. Various genera of microbes including both bacteria and fungi have been reported to show tolerance to higher salinity (even above 1000 mMNaCl) and in return supporting growth of plants (Mishra et al. 2018).

**Flood stress** The application of beneficial soil microbes has shown promising results in upgrading the plant health under flooding stress. Plants inoculated with ACC deaminase producing microbes show lower ethylene concentration thereby protecting them from damages caused due to ethylene. The absence of oxygen in waterlogged plants also affects the development of nodules and nitrogenase activity (Day and Copeland 1991). Under such conditions rhizobia which can use nitrogenous oxides as terminal electron acceptors can survive and support the nodule formation and also improve nitrogen fixing ability (Zablотовicz et al. 1978; Tewari and Arora 2016). AMF are also reported to be efficient candidates in ameliorating flooding stress in plants (Grover et al. 2011). Tanner and Clayton (1985) found that submerged aquatic plants with mycorrhizal colonization showed 20% more P than non-colonized plants. Under flooding conditions the fungal mycelium spread the root systems so that more nutrients are assimilated and better absorption of water can occur (Harley and Smith 1983). Successful AM colonization has been observed in rice, soybeans, *Populus*, *Salix*, and *Nyssa* spp. growing in flooded soils (Keely 1980; Dhillon and Ampompan 1992; Tewari and Arora 2016). The population of cyanobacteria are also profoundly found associated with paddy crops like rice. These efficient cyanobacteria include *Nostoc linkia*, *Anabaena variabilis*, *Aulosira fertilisima*, *Calothrix* sp., *Tolyphothrix* sp., and *Scytonema* sp. The association of cyanobacteria with crops plays an important role in enhancing soil fertility and fixing nitrogen under waterlogged conditions. The aforementioned genera have been used as paddy crop inoculants under both upland and low land conditions (Sahu et al. 2012).

**Combating biotic stress** Plant pathogens including bacteria, fungi, viruses, nematodes and insects negatively influence the crop productivity. However, PGPM with biocontrol traits are used as biopesticides and have proved to be quite effective in protecting plants/crops against phytopathogens (Mishra et al. 2015). Among the different types of biocontrol agents used 51% are microbial pesticides, 19% beneficial insects, 16% microbial soil treatment, 14% other biochemicals (https://cen.acs.org/articles/92/i37/Growing-Profits-Microbes.html?hr=1571492113). Among various types of microbial biopesticide products available in the market 60% are bacterial, 27% fungal, 10% viral and 3% others (Kabaluk et al. 2010). The microbial biocontrol agents provide defense against pathogens through cellular burst, cell wall destruction, synthesis of secondary metabolites such as antibiotics, affecting fungal germination and hyphal extension through production of antifungal compounds (Kumar and Verma 2017; Van Agtmaal et al. 2015). Other antagonistic approach of PGPM involves synthesis of lytic enzymes which are able to hydrolyze various polymeric compounds like cellulose, chitin, hemicellulose, proteins, DNA of phytopathogens (Beneduzi et al. 2012). Lytic enzymes have successfully been reported to destroy oomycetes of fungi and inhibiting their spore germination and germ tube elongation (Frankowski-Lorito et al. 2001; Saraf et al. 2014).
Different secondary metabolites are also involved in biocontrol against phytopathogens, nematodes and insects such as hydrogen cyanide (HCN), antibiotics (phenazine-1-carboxylic acid (PCA), phenazine-1-carboxamide (PCN), pyrrolnitrin, pyoluteorin, 2,4 diacetylphloroglucinol (DAPG), Oomycin A, Cepaciamide A. Production of EPS, biosurfactants, chelation of P, Zn, Fe and niche exclusion are also involved in biocontrol (Banat et al. 2010; Pathak et al. 2017). Several bioformulations involving microbes have also now been developed for combating nematodes and weeds across the globe (Harding and Raizada 2015).

Biocontrol agents can also initiate defensive mechanisms in host plants against phytopathogens, also known as induced systemic resistance (ISR) and systemic acquired resistance (SAR). ISR involves pathways regulated by jasmonate and ethylene while SAR involves gene expression and accumulation of pathogenesis related (PR) proteins and salicylic acid (SA) (Bari and Jones 2009; Salas-Marina et al. 2011). The palpable role played by microbes in combating phytopathogens has been extensively reported along with various registered microbe-based biopesticide products that are finding agricultural applications (Kakar et al. 2014). Microbial inoculants have successfully curbed a variety of phytopathogens including fungi, bacteria, insects, nematodes and have proven to be ecofriendly as well. Figure 9 depicts the increasing trend of biological market share of agrochemicals over the years.

**Biotechnological solutions and future prospects**

Biotechnological tools and applications can provide solutions to an array of environmental issues and problems. With the introduction of transgenic cultivars, management of pests has become possible in a more specific way than with the use of herbicides and pesticides. A global meta-analysis study conducted by Klümper and Qaim (2014) reveals that the advent of genetic engineering technology reduced the use of pesticides by 37% whereas increment in yield of crops was reported by 22% from 1995 to 2014. These genetically modified (GM) crops being narrower in their mechanism of action do not affect non-target organisms. The toxins that are produced by such crops in order to combat against pests are only produced within tissues of plants and are targeted against the pathogens only, hence not causing harm to the ecosystem (Lozzia 1999; Dively and Rose 2002). Insect resistant Bt crops such as Bt maize and Bt cotton are excellent examples which are used as green substitutes to broad spectrum synthetic pest controls. Similarly, there are GM herbicide tolerant (HT) varieties (like soybean, canola, sugar beet). Crops like papaya and squash have been engineered to combat against viral diseases (e.g. against ring spot in papaya) (Brookes and Barfoot 2015). The global data on GM crops shows a substantial increase at farm levels which accounts for about $150.3 billion between the year 1996–2014 with net economic profit equivalent to $17.7 billion in 2014 (Taheri et al. 2017).

Genetic engineering is also being used successfully in remediation of contaminants. Microorganisms of interest are engineered to enhance the process of bioremediation (via improved cell membrane transportation and reduction or expansion of substrate spectrum of toxic compounds like organophosphates) (Yong and Zhong 2010). Multifunctional bacteria known as “superbugs” have been developed which have capability to degrade wide range of pollutants (Yan et al. 2006; Jiang et al. 2007). Under bioprocess engineering, there are several methods by which biodegradation is performed such as additional augmentation of carbon sources or its intermediates at polluted sites, which improves the degradation process by the development of bacterial population or through co-metabolism (Yong and Zhong 2010). Signal transduction has been an effective technique for biodegradation processes like aromatic pollutants and treatment of wastewater. Many bacteria capable of quorum sensing produce a signal during degradation processes using acylated homoserine lactone (AHL). This type of cell to cell mediated signaling enable bacteria to carry out gene expression and regulation of phenotypic properties like EPS secretion and biofilm formation which help in degradation (Fuqua et al. 1996; Dobretsov et al. 2009).

A new technique of bioremediation using transposon-mediated ISMoB (it is an integration of genes into microbial...
Microbes with resistant genes are isolated and are checked for the particular locations of their resistant operons. It is then determined for the vectors to carry out transfer of transposons between species. If in case, the microbe lacks the presence of vector, it is first transformed with suitable conjugative plasmids. The microbes possessing resistant transposons are introduced into polluted sites and act as donors of resistant operons. The process of horizontal gene transfer between non-indigenous and indigenous microbes is enhanced by supplementation of nutrients and activation of ISMoB. This results in effective mitigation of contaminants by indigenous microbes (Garbisu et al. 2017; Matsui and Endo 2018). The best example of such a process was observed in the study by Matsui and Endo (2018) for amelioration of mercury contamination in Japan (minamata disease). Likewise, recombinant DNA technology has helped plants in getting rid from serious heavy metal pollutants. An arsenate antiporter PvACR3 was expressed in Arabidopsis which resulted in arsenic resistance in the plants and seeds engineered with such an antiporter showed greater tolerance even at higher concentrations (Clemens and Ma 2016). A recent multifaceted hybrid technique known as bioelectrochemical system (BES) has garnered considerable interest in overcoming limitations of the in situ bioremediation methods of various kinds of wastes such as organic, sludge, wastewater, heavy metals and VOCs along with generation of energy (electricity, hydrogen or other forms of useful chemicals) (Srikanth et al. 2018). Microbial fuel cells, microbial electrolysis cells and microbial desalination cells are its other types and are becoming a sustainable approach. Bioelectrical wells have been designed by researchers for remediation of contaminants using these microbial electrochemical technologies (Palma et al. 2017).

Biofiltration is another technique used for removal of pollutants such as PAHs, PCBs, volatile organic compounds (VOCs), and treatment of wastewater. The major advantage of a biofilter is that it’s a cost effective technique and generates no harmful byproducts like those in traditional techniques e.g. incineration (http://www.biofilter.com/). Biotrickling filter is a common example of a biofilter (Chaudhary et al. 2003). On the other hand, biosensor, a biological probe made up of either whole cell, enzyme, nucleic acids or antibodies are also being used in monitoring environmental pollutants in real time which makes it easier to locate the specific pollutant like metal(loid) and degrade or transform them accordingly (Rodriguez-Mozaz et al. 2006; Nigam and Shukla 2015). They are also used to detect pathogens and as bioindicators e.g. coliform for sewage contamination (Ercole et al. 2003).

Nowadays, ‘omics’ technologies are being explored in order to preserve sustainability of the environment. Metagenomics is one such example which is being used in many environmental applications such as in bioremediation of pollutants by detecting those bacteria which have not yet been cultured but have potential to combat toxic contaminants of land and water bodies (Gupta and Sharma 2011). With recent developments, genome analysis has made it easier to identify the threatened or endangered species through the study of their DNA. Population structure, genetic variations and recent demographic events in species can be easily investigated using population genomic approaches (Khan et al. 2016). The next generation sequencing (NGS), a high throughput genomics has come up with new kind of genome editing which does not require insertion of foreign DNA, rather the gene of interest is directly modified (Schiml and Puchta 2016). This kind of genome editing is simple, low in cost and versatile. CRISPR-Cas9 (Clustered regularly interspaced short palindromic repeats and Cas operon) (Lowder et al. 2015) genome editing is an excellent example in this context which performs with precision and is being explored by several conservationists for agricultural attributes like development of new plant varieties which are capable of producing high quality and sustainable products (Weeks et al. 2016; Arora and Narula 2017). The advantage of genome editing is in providing resistance to endangered plant and animal species to withstand phytopathogens and other stresses. Gene editing to combat abiotic factors, can enable keystone species to survive in the stresses caused by climatic change (Corlett 2017).

Metabolites of microbial origin can be very useful for industries and can be better and green alternatives for dangerous chemicals and products. Another application of metagenomics is in the industrial biotechnology where metagenomic DNA libraries offer possibility of identification of huge range of metabolites, biomolecules and industrially important enzymes from uncultivated bacterial communities through gene expressions (Simon and Daniel 2009). Many bioactive compounds, enzymes, small biosynthetic gene clusters and anti-microbial proteins have been recently identified with metagenomic approaches (Banik and Brady 2010). Genetic engineering along with several tools like metabolic engineering, cell free technology and alterations in nutrient and growth are being used to produce specific enzymes which help in obtaining required products in eco-friendly manner (Ullah et al. 2016). Globally, industrial market of enzymes was estimated to be 3.3 million dollars in 2010 and reached around 4 billion dollars in 2015 (Gurung et al. 2013). Metagenomic analysis has recently identified novel lignocellulosic microbial enzymes from bovine rumen microbiome for the production of biofuel which are capable of degrading forage (Brulc et al. 2009). Other than dairy, pharmaceuticals, textiles, detergent and baking industries, biotechnology has helped in exploiting these biocatalysts in solving different environmental problems. Lipases produced by soil microbes have degradation properties which
are being used in oil contaminated sites. These enzymes also act as indicators of oil contamination in freshly contaminated soils (Margesin et al. 1999; Amro and Soheir 2009). Fungal lipases are used in coastal areas for oil spill degradation and the restoration of the contaminated sites (Prasad and Manjunath 2011; Gurung et al. 2013). Fungal and bacterial cellulases are capable of removing ink which helps in its degradation (Bahera et al. 2017). They are produced during paper and pulp production processes and are better alternatives to conventional harmful chemicals used while deinking (Rosenfield and Feng 2011). Laccases, peroxidases, dioxygenases are another class of microbial enzymes produced by certain bacteria and fungi that catalyze the oxidation of various phenolic and aromatic compounds (Karigar and Rao 2011). Cholesterol oxidase, a microbial enzyme produced from submerged fermentation process is in high demands in 2011. Microbial enzymes are playing a crucial role in maintaining the sustainability and productivity of ecosystems. Currently, there is a growing trend to use novel microbial enzymes to help in reducing the waste problem. In this direction, Mallinson et al. (2018) discovered a new class of cytochrome P450, able to work on a wide range of molecules. They propose that these enzymes can convert plant waste into sustainable and high-value products such as nylon, plastics, chemicals, and fuels. Pre- and post-genomic studies confirmed the unusual potential of several fungal P450 s enzymes in degradation of toxic environmental chemicals including persistent organic pollutants (POPs) (Bhattacharya and Yadav 2018). Recently integrated approaches of genomic, homology modeling and docking studies of microbial nitrilase were found very useful in the construction of engineered nitrilase used in cyanide bioremediation (Park et al. 2017). A lot more is needed to be explored in relation to microbial enzymes from cultural and non-culturable microbes.

Apart from enzymes, other microbial metabolites can also be explored in a number of ways and industries for eco-friendly approaches. Metabolomics can be applied for detection and production of useful microbial metabolites which have not been explored as yet. Genomic sequences of most of the known and studied microorganisms confirm that still we have not been able to identify many gene clusters responsible for secondary metabolites. Upcoming databases such as Integrated Microbial Genomes Atlas of Biosynthetic Gene Clusters (IMG_ABC) are designed for identification of gene clusters for microbial secondary metabolites in bacterial metagenomes. Such databases can be very useful for identification of novel metabolites with industrial uses (Mishra and Arora, 2017).

Microbiome, traditionally, is the genomic study of the microbial community living in a well defined habitat and also the environmental traits associated with it (Betts 2011). A project called ‘Earth Microbiome Project’ was started in 2010 to study the characteristics of the structure, diversity and distribution of the microbial ecosystems around the globe and has a collection of 30,000 samples. The samples include diverse ecosystems such as animals, humans, plants, terrestrial, marine, freshwater, air, sediments, constructed environment and even the intersections of such environments (Gilbert et al. 2014). The emerging microbiome concept has a lot of potential to combat against biodiversity losses and other negative attributes which affect the homeostasis of the host environment (Aguilar-Pulido et al. 2016). If exploited appropriately, this study could improve the productivity of crops and many other plant species in coming future by providing resistance against biotic and abiotic stresses (Mendes et al. 2013).

Biofuels are an important success story gaining a lot of attention in recent times. The production of biofuels has increased by 8% since the year 2000 and has equated to 4% of global transport fuels in 2015 (BP Statistical Review of World Energy 2015). Although biofuel production is still in nascent stage but its production and use is expected to grow in coming time. Biofuels like biomethanol, bioethanol, biobutanol, biodiesel and biogas have already been commercialized (OECD 2011; Immerzeel et al. 2014). Nowadays, biofuels from cellulosic feed stocks and agricultural and forest residues have further settled the debate on controversy related to edible feed stocks and are reported to reduce GHG emissions (USEPA 2011). Advances in production of microbial enzymes like cellulases have further improved their efficiency (Knauf and Moniruzzaman 2004; Ezeonu et al. 2012). Amended fuels like biodiesel-diesel blends and ethanol-gasoline blends are being commercialized since past few years to further minimize GHG emissions and other toxic pollutants (Manzetti and Andersen 2015). Likewise, production of biogas through microbes from solid waste management, wastewater treatment and composting are now being utilized successfully in order to make use of biodegradable wastes to generate useful source of bioenergy. Dye sensitized solar cells (DSSC) are yet another interesting alternatives which are used successfully as a substitute to photovoltaic cells with significant conversion efficiency (Yum et al. 2012). Bacterial dyes are utilized in such cells which makes them environment friendly. Polar Regions are a huge source for pigment producing bacteria and algae and have now been explored to make use of such bacterial DSSC which could minimize use of fossil fuels (Montagni et al. 2018). Uses of cyanobacteria which are oxygenic phototrophs and are known to dissipate hydrogen gas are also an effective alternative energy source (Tiwari and Pandey 2012). These microbes through their multienzyme systems (hydrogense
and nitrogenase) are considered as potential candidates for production of biohydrogen as energy source (Oncel 2013). With recent developments in biotechnology such as bio-process engineering, optimization in bioreactor design and integration of metabolic engineering the production of this clean fuel is expected to increase in future (Gangl et al. 2015). In fact hydrogen based biofuels are believed to be the greenest alternatives with zero CO₂ emission. Hydrogen based biofuels are hence considered fuels of future. A growing demand in transportation and aviation sector has made it necessary to develop a wide range of biofuels. Therefore omics approaches are also being applied to develop fourth generation biofuels which would be derived from engineered organisms and would prove to be cost effective, sustainable and a cleaner approach for future.

Bioplastics are another example in this context which are produced from biomass (plant products like sugarcane, potato starch or cellulose from trees) and could be a better alternative to reduce pollution of landfills. Like plants, microbes (bacteria and yeasts) are also known to produce bioplastics in form of poly (3-hydroxyalkoanates) (PHA), such as poly-β-hydroxybutyrate (PHB) (Luengo et al. 2003). The first commercialized bioplastic was produced as Biopol by ICI Ltd in 1982 (Angelova and Hunkeler 1999). Nowadays, with help of metabolic genetic engineering, industrial wastes are being utilized as readily available carbon sources for high value production of bioplastics through microbes (Jiang et al. 2016). These bio-based polymers due to their wide range of biotechnological aspects and unique characters such as biodegradability, low carbon footprint, less manufacturing costs and above all being eco-friendly have made them extremely important compounds for future (Chen 2014).

The vigorous developments of biotechnological tools and bioengineering methods have paved way towards sustainable and green future. Further exploitation of such techniques such as integration of metagenomics, metatranscriptomics, metaproteomics and metabolomics can be very useful in near future to study and predict the microbial diversity and functions of an ecosystem (Aguiar-Pulido et al. 2016). The need is to use these high throughput technologies in habitats for determining the microbial abundance, dominant types, functions, and shifts in relation to natural and anthropogenic interferences. Emerging applications of Environmental-DNA (e-DNA) metabarcoding in integration with high throughput sequencing are rising as significant molecular tools which help in analyzing species diversity from different ecosystems and in their bio-monitoring. This method could completely transform surveying of plant and animal communities in any ecosystem because of its non-invasiveness and eco-friendly approach (Deiner et al. 2017).

Research priorities including incorporation of new technologies for harnessing plant microbiomes is necessary in modern agricultural practices especially in light of global climate change (Busby et al. 2017). The integrated knowledge of plant-microbe associations will offer desired traits in plants such as enhanced disease resistance towards phytopathogens, greater drought and salt tolerance and better uptake of nutrients. Agricultural bioinformatics tools could also be used in improving our knowledge in nutritional value of cereals or in analyzing plant genome for susceptibility towards biotic and abiotic stresses (Kumar et al. 2018b). Recently, use of satellite imagery and other spatial datasets in agriculture systems have been initiated which provide comprehensive details about farm planning, assessment of crop yield loss by observing nutritional disorders, missed fertilizer stripping, damage from pest or phytopathogens etc. (https://www.geoimage.com.au/industries/agriculture). Figure 10 depicts some of the useful and applicable biotechnological solutions for maintaining environmental sustainability.

Biotechnological approaches are thus the approaches of future with both low input and high input methods but having great potential to revolutionize the scenario of environment sustainability through the use of latest tools and techniques and mainly microorganisms and their genes, enzymes or metabolites for green uses. A lot more needs to be explored in this front in the near future.

**Conclusion**

Survival of mankind rests on the sustainability of the environment. Anyhow, we have to save our environment and ecosystems for sustaining the life and particularly the mankind on the blue planet. In the present scenario the rate of damage and destruction is far more than the reclamation or healing capacity of the ecosystems which needs to be reversed very quickly. Anthropogenic activities are causing great damage to the planet and hence we need to shift to the green alternatives so as to heal the ecosystems and bring them back to normalcy. Biological tools and entities such as microorganisms and plants can play a major role in reclamation of polluted ecosystems and reverse the impact of global warming and climate change. But these need to be implemented at global level. The SDG Report 2018 of the UN, projects the agenda for 2030. It is clear from the report that major cities are facing the problem of severe air, soil and water pollution and these need to be tackled very urgently. Accelerated and swift actions are required from countries, international organizations and even at individual levels so as to implement the green solutions and policies. Out of the 17 goals of the UN report and 2030 targets, 13 directly target the sustainable environment and these need to be achieved by biological/natural alternatives for food production and security, green fuel, sustainable management of water resources...
and treatment of polluted water, clean and green energy, sustainable economic growth and sustainable employment opportunities, sustainable industrial growth and pollution management, sustainable and green cities, sustainable production of consumer goods, combating climate change, conservation and sustainability of marine biodiversity and terrestrial ecosystems, combat desertification, salinization and land degradation, control biodiversity loss, inclusive growth by involving all the stakeholders and strengthen global partnership to achieve all these goals. Sustainability is thus the keyword at present and if we do not work and wake-up right now things can go beyond our control. Green and low input biotechnological solutions can provide answers to many of these problems which were discussed and exemplified in this review. Still, we have only touched the tip of the iceberg and a lot needs to be done and explored. Planet earth has huge diversity and luckily despite great destruction most of it is still intact which can be used with latest biotechnological tools and techniques to resolve the problems. Need is the holistic participation of all the stakeholders and will power to overcome hurdles and implement the green technologies for betterment of the present and hand over a healthy planet to the future.

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