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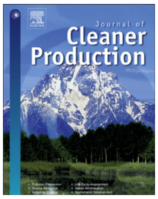

The role of microorganisms in achieving the sustainable development goals

Adenike A. Akinsemolu [a], [b], [*]

[a] The Green Institute, Ondo, Ondo State, Nigeria
[b] Department of Microbiology, Federal University of Technology, Akure, Ondo State, Nigeria

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ABSTRACT

In January 2016, the 2030 goals for sustainable development were set by the United Nations for achieving environmental, social and economic growth through green methods and cleaner production technologies. The most significant targets of these goals are the fulfillment of basic human needs and desires, since essential human necessities like food, cloth, shelter and health care are still not accessible to a majority of the people despite the great pace in the world's economy. Increased waste products and continuously depleting natural resources have diverted human attention towards efficient green and clear production technologies. The Sustainable Development Goals (SDG) aim at providing these fundamental necessities to everyone through the intelligent use of sustainable science. In this perspective, microorganisms, which are vital to the maintenance of life on earth, can play a major role. Although most people focus primarily on the disease-causing capabilities of microorganisms, there are numerous positive functions that microbes perform in the environment and hence, a need to explore the microbial world astutely as it can contribute tremendously to sustainable development. In this review, the integration of microbial technology for the achievement of SDGs is being put forth. The scope of the use of microorganisms, points of their control, methods for their better utilization and the role of education in achieving these targets are being discussed. If the society is educated enough about the ways that microbes can affect our lives, and if microbes are used intelligently, then some significant problems being faced by the world today including food, health, well-being and green energy can be adequately taken care of.

1. Introduction

Our current practices, including the indiscriminate use of chemicals, increased employment of non-renewable sources of energy and uncontrolled generation of waste products in every possible industrial process, has posed a large threat to the sustainability of the environment. The world now has a greater responsibility to adopt sustainable measures, cleaner production and green technologies so that the ecology of the Earth may be conserved for future generations.

“We don't have a Plan B, because there is no Planet B” says Ban Ki-Moon, the United Nations Secretary-General in 2016 during the United Nation's (UN) 22nd conference on climate change in Marrakesh, Morocco (Ki-moon, 2016).

To collaboratively make an effort in this direction, 193 countries agreed to the 17 Sustainable Development Goals (SDG), which is a UN's sponsored effort for a sustainable economic development of the world (Costanza et al., 2016). These goals have been classified into five (5) subgroups -People, Planet, Prosperity, Peace and Partnerships (Fig. 1). The SDGs aim at developing the solutions which can enable economic and societal development, but not at the expense of environmental damage. Rather, these efforts emphasise on the environmental protection by preventing and controlling the unlawful exploitation of natural resources (United Nations, 2016a).

Microorganisms have colossally diversified. They play important roles in the environment, as well as being crucial in series of green processes and cleaner technologies, ranging from biogeochemical cycles to various industrial productions. If microorganisms are used judicially, they can contribute significantly to the sustainable development (Kuhad, 2012) (Table 1). A common goal of the world now is the use of cleaner production and green technologies, as

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[*] The Green Institute, Ondo, Ondo State, Nigeria.
E-mail address: akinsemoluaa@greeninstitute.ng.

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Fig. 1. The five subgroups of the Sustainable Development Goals.

well as the preservation of natural resources. Surprisingly, despite the overwhelming advantages of microorganisms in the various contexts of sustainability, it is often trivialized in the discourse of operationalizing the SDGs. Against this background, this paper argues that microorganisms play a fundamental role in achieving the SDG and thus, the paper aims to demonstrate these roles and importance.

To achieve the aim of demonstrating the value of microorganisms in the context of attaining the SDGs therefore, the arguments in this paper are structured and discussed in four main sections. Following section one which is the basic introduction, is section two which is concerned with the discourse of the role of microorganisms in the context of the predetermined seventeen goals of the sustainable development agenda. This section draws on the appraisal of the existing professional perspectives on the discourse of microorganisms to demonstrate its role in each context of the seventeen goals of the UN sustainable development agenda. The summary of this section is illustrated in a table (see Table 2). Section three highlights the contemporary research lacuna in the discourse of microorganisms and the SDGs and posits recommendations for the furtherance of such research in the future. The last section in this paper is the conclusion which critically draws on the arguments generated in this research to posit positions which argues for the inclusion of microorganisms into the means of operationalizing the SDGs in every context, in both developed and developing countries.

2. Microbes and the sustainable development goals

2.1. SDG 1: No poverty

According to World Health Organization (2017a, b, c, d), poverty is associated with undermining of a range of fundamental human attributes, including health. Poverty renders people unable to access the basic requirements, malnourished and with a significant risk of disability and illness. These handicapping and diseased conditions further cause low earning capacity, reduced productivity and lower quality of life all of which creates a vicious cycle of poverty (World Health Organization, 2017a). When compared to the poor and unhealthy people, healthy populations survive longer, are more productive and therefore contribute positively to the economic progress of the world.

Poverty and microorganisms very much go hand-in-hand, being the former the chief cause of microbial related deaths. Nearly 12.6 million people are dying each year due to an unhealthy environment (World Health Organization, 2016a). Globally, it has been found that 52% of deaths in low-income countries are attributed to communicable diseases, nutrient deficiencies and maternal causes, as compared to only one to two percent of such mortality occurring in the rich, developed countries (World Health Organization, 2017b). This throws the light on the stark reality of how microbial infections are affecting the lives of those who do not have access to food and healthcare, and are unable to maintain proper hygiene (Irwin et al., 2006). Indeed, the diseases of such conditions, disproportionately affecting the poor and often remaining mis- or underdiagnosed, are referred to as the “infectious diseases of poverty” (Alsan et al., 2011).

A major way to curb this cycle of poverty and infectious diseases is to raise the research standards and fund the development of new drugs, diagnostic methods, monitoring programs, treatment regimes and newer technologies for preventing the transmission of these infections. Raising awareness among the people about maintaining proper hygiene and maternal health can also immensely contribute in controlling the microbe-caused poverty throughout the developing nations since the preservation of hygienic conditions has been shown to favour the controlled outbreak of infections in hospital, as well as in general habitat environments (Drexler, 2010).

Another significant relationship between poverty and microbes is the development of antimicrobial resistance. Emerging drug resistance has outpaced the development of new drugs, having the World Health Organization (2000) cited poverty as one of the major forces that have driven the evolution of superbugs. One of the factors which are responsible for the current situation is the poorly regulated manufacturing and dispensation of antibiotics. Easy availability of these substances, self-medication and procuring the drugs without a prescription leads to the inadequate use of the antimicrobial compounds. This puts selective pressure on the microorganisms to evolve, thereby developing resistance (Planta, 2007). Antimicrobial resistance in microbes like *E.coli, Klebsiella* sp., *MRSA, Streptococcus,* and *Enterococcus* has been linked to the prevalence of poverty, poor governance and corruption (Alvarez-Uria et al., 2016; Collignon et al., 2015; Sosa et al., 2010). This problem can be managed by restricting the dispensation of over-the-counter antimicrobials, regulating their manufacturing, providing quality drugs to the people and promoting the awareness for legal use of antimicrobial drugs (Lambert et al., 2007; Planta, 2007).

Microbes are not only the foes, but they can also be the friends. Educating and training poor people about the use of “green” microorganisms for generating income is an approach to make them self-sufficient. Practices like the production of Gobar Gas or traditional microbial fermented food products like pickles, vinegar, sake, and kumis may help the poor people in generating a source of income by learning the proper skills required for translating these techniques into an actual business. Governments can play a role in this by organising free campaigns and small-scale skill development programmes, as well as by subsidising the equipment required to set them up (Marshall and Mejia, 2012). An example of using fermented food products for sustainable development are the traditional products of Nigeria like Ogi, Garri, Pito, and Iru, which have been described as sustainable methods of reducing poverty and boosting societal development (Adesulu and Awojobi, 2014). Fermented beverages such as Jamun and *Aloe vera* wine and other ethnic fermented drinks like Chyang also provide a sustainable means of boosting employment and controlling poverty (Ray et al., 2016).

Harnessing microbes may serve two purposes for the people: first, they will be able to produce their foods; second, they will be

Table 1
Summary of the role of microorganisms in achieving SDG 1- 17.

SDG	Goal	Application of Microorganisms	References
1	No Poverty	**1. Income Generation** **Production of Gobar Gas** by methane-producing organisms such as *Methylosinus, Methylocystis, Methanomonas, Methylomonas, Methanobacter, and Methylococcus*), traditional food in Nigeria like Ogi, Garri, Pito, and Iru, and **Vinegar** (Lactic Acid Bacteria and Yeast).	(Adesulu and Awojobi, 2014; Bhutto et al., 2011; Encyclopedia.com, 2017; Rainieri and Zambonelli, 2009)
2	Zero Hunger	**2. Fermentation** **Pickles** (*Leuconostoc mesenteroides, Lactobacillus plantarum, Pediococcus cerevisiae*), **Milk** (*Lactobacillus*), **Tempe** (*Acetobacter and Rhizopus oligosporus*), **Cheese** (*Penicillium roqueforti, Streptococcus salivarius subsp thermophilus*), **Soy Sauce** (*Aspergillus oryzae, Aspergillus soyae, Aspergillus glaucus*), **Yogurt** (*Lactobacillus delbruekii subsp bulgaricus, Streptococcus salivarius subsp thermophilus*) and **Bread** (*Saccharomyces cerevisiae*) **3. Soil Fertility** Arbuscular mycorrhizal symbiotic fungi and phosphate-solubilizing microorganisms such as *Pantoea agglomerans, Microbacterium laevaniformans and Pseudomonas putida*	(Beuchat, 2008) (Averill et al., 2014; Khan et al., 2009)
3	*Good Health and Well-being*	**4. Prebiotics and Probiotics** (*Lactobacillus acidophilus, Aspergillus niger, Saccharomyces carisbergensis*) **5. Development of New Drugs** Penicillin (*Penicillium notatum*) Chloramphenicol (*Streptomyces venezuelae*) Griseofulvin (*Penicillin griseofulvin*) **6. Immunoregulation in Humans** (*Bifidobacteria and Lactobacilli*) **7. Gastrointestinal Flora Prevention of diseases like gastroenteritis** (*Prevotella, Bacteroides, Faecalibacterium prausnitzii and Ruminococcus*) **8. Controlling Pollution related diseases** *Burkholderia, arthrobacter, Chromobacterium, Micrococcus, Candida, Pseudomonas, and Bacillus*	(De Vrese and Schrezenmeir, 2008; Manning and Gibson, 2004; Mizock, 2015; Wang, 2009; Williams, 2010) (Balbi, 2004; Bergmann and Sicher, 1952; Finkelstein et al., 1996; Fleming, 1944; Lerner, 2004; Rosefort et al., 2004) (Romano-Keeler and Weitkamp, 2015) (Kaplan et al., 2011) (Das et al., 2011; Zabochnicka-Światek and Krzywonos, 2014).
4	*Quality Education*	**9. Teaching, Research and Innovation** • Built Environment, Molecular Biology, Education on Infant Immunity (breastfeeding and hygiene) • **Enzymes:** *Humicola lanuginose* **(thermostable lipase)**, *Aspergillus niger* **(lipase, protease, cellulase, and xylanase)**, *Aspergillus flavus* **(cell-bound lipase)**, *Mucormiehei* **(lipase)**, *Bacillus megaterium* **(organic solvent tolerant lipase)**, *Cellulomicrobium* **(alkaline protease and keratinase)**, *Geobacillus thermodenitrificans* **(thermostable lipase)** **10. Renewable energy sources for reading in rural communities** Microbial Fuel Cell, Biogas	(Cortese, 2003; O'Sullivan et al., 2015; Simonneaux, 2000). (Gautam et al., 2009; Logan et al., 2006; Mshandete and Parawira, 2009; Nagamani and Ramasamy, 1999; Santoro et al., 2017)
5	*Gender Equality*	**11. Sexual and Reproductive health** • About 290 million women have a human papillomavirus (HPV) infection • STIs have grave reproductive health consequences such as infertility or mother-to-child transmission • In 2012, more than 900 000 pregnant women were infected with syphilis resulting in roughly 350 000 adverse birth outcomes including stillbirth **12. Income generation** Through production and preservation of foods and pharmaceutical products, as well as the production of Gobar Gas and biofuel. **13. Empowerment (STEM)** A high percentage of women graduating from these fields end up employed in other areas **14. Well-being of the family** Promoting education among women will improve the well-being of their children, families, and society	(de Sanjosé et al., 2007; Newman et al., 2013; World Health Organization, 2016b) (Palanithurai, 2007; Rao, 2005) (Xie and Killewald, 2012) (Roudi-Fahimi and Moghadam, 2003)
6	*Clean Water and Sanitation*	**15. Controlling Poor-Sanitation Related Diseases** Microbes are essential in the production of Rotavirus vaccine, zinc and vitamin A and in improving water sources. **16. Regulation of microbial load** *Escherichia coli, Salmonella, Vibrio*, and *Shigella* can significantly contribute in controlling water-borne diseases	(Chola et al., 2015) (Cabral, 2010)
7	*Affordable and Clean Energy*	**17. Electricity generation (Bioenergy and Biofuel)** • *Botryococcus* can store up to 50% of the biomass in the form of long-chain hydrocarbons.	(Hannon et al., 2010) (Lal, 2013) (Appels et al., 2011; Elshahed, 2010)

(*continued on next page*)

Table 1 (*continued*)

SDG	Goal	Application of Microorganisms	References
		• Utilizing of organic matter by *Shewanella oneidensis* and *Geobacter sulfurreducens* to produce utilizable electricity. • Utilizing waste products such as sewage sludge, municipal solid waste and agricultural waste by *Trichoderma, Aspergillus, Penicillium*, and *Clostridium* to produce bioenergy.	
8	*Decent Work and Economic Growth*	**18. Research and development** • Dinoflagellate *Karlodinium veneficum* is under investigation for its potential uses in human health. • Organisms like *Penicillium* produces the first discovered antibiotic: Penicillin and bacteria like *Streptomyces sp.* produce the aminoglycoside antibiotics. • In Denmark, biogas production policy contributes to the nation's bioenergy concept and reduction of carbon emissions. • Biogas stove providing jobs in Sub-Sahara Africa	(Waters et al., 2010) (de Lima Procópio et al., 2012; Fleming, 1944; Hersbach, 1983; Lerner, 2004) (Mæng et al., 1999) (Tumwesige et al., 2014)
9	*Industry, Innovation and Infrastructure*	**19. Biofertilizers** *Pseudomonas and Rhizobia* **20. Microbial products** **Vitamin C** (*Corynebacterium sp.*), **Coenzyme** (*Brevibacterium ammoniagenes*), **Riboflavin fermentation** (*Eremothecium ashbyii, Ashbya gossypii, Bacillus sp.*), **Vitamin B12** (*Propionibacterium shermanii, Pseudomonas denitrificans*), **S-Adenosylhomocysteine** (*Alcaligenes faecalis*), **Biotin** (*Serratia marcescens, Bacillus sphaericus*)	(Mohammadi and Sohrabi, 2012; Sahoo et al., 2013; Vessey, 2003) (Shimizu, 2008)
10	*Reduced Inequality*	**21. Agricultural and land management practices** Women can be taught the importance of soil microflora like *Burkholderia, Pseudomonas, Rhizobium, Trichoderma, Bradyrhizobium*, and *Azospirillium* in improving crop productivities	(Pereg and McMillan, 2015)
11	*Sustainable Cities and Communities*	**22. Ecology of urban cities and Solid waste management** Composting of the solid waste uses microorganisms like *Pseudomonas, Bacillus, Microbispora, Actinobifida*, and *Thermoactinomycetes* for converting its organic constituents into useful end products.	(Finstein and Morris, 1975; King, 2014)
12	*Responsible Consumption and Production*	**23. Responsible production through bacterial cellulose** Bacterial Cellulose (BC) from *Komagataeibacter* can be used in the production of fuel and Li-ion batteries **24. Microbial and Environmental education** Personal hygiene, cleanliness, restricting self-medications, separating organic and inorganic household waste, and minimizing the use of fossil fuels. **25. Bioremediation** Bioremediation is an fascinating and successful cleaning technique for polluted environment.	(Jang et al., 2017) (Barberán et al., 2016; Chawla and Cushing, 2007; Dewan et al., 2010; Tilbury, 1995) (Atlas and Philip, 2005; Ayotamuno et al., 2006; Karigar and Rao, 2011; Rajendran et al., 2003; Rosenberg and Ron, 1996)
13	Climate Action	*26. Biogeochemical cycles* *They are key drivers in biogeochemical cycles like nitrogen, carbon and phosphorus cycles.* **27. Nitrogen fertilizers** Microbial community structure is important when assessing the impact of environmental perturbation (e.g. nitrogen fertilizers) on biodiversity loss and ecosystem functioning. **28. Biofuel production** Algae like *Saccharomyces* or modified *Escherichia coli* can be used for third-generation biofuel production. It is practical, economically-feasible, and achievable solution for the development of sustainable environment (Singh et al., 2010).	(Auguères and Loreau, 2015; Falkowski et al., 2008; Grandy et al., 2016) (Mohanty et al., 2006) (Singh et al., 2010)
14	*Life below Water (Marine Ecosystems)*	**29. Aquaculture** Microbes can effectively boost the production of fisheries by controlling the pathogenic outburst and water quality, as well as regulating the environmental impact	(Martínez-Córdova et al., 2016)
15	*Life on Land (Ecosystems)*	**30. Ubiquitous functions** Microbes stabilize the soil structure, enable nutrient uptake by plants, control pests and diseases, decompose organic material and degrade harmful chemicals, as well as being an indicator of the soil health.	(Wachira et al., 2014)
16	*Peace, Justice and Strong Institutions*	**31. Combating bioterrorism** Microbial forensics can be used to trace perpetrators and sources of biohazard, thereby being as a powerful tool for combating bioterrorism	(Budowle et al., 2005; Sijen, 2015)
17	*Global Partnerships for Sustainable Development*	**32. Capacity building on trade-related aspects** The benefits of microbes and microbial technology can only reach the masses through globalization and overcoming land barriers. This will	(Chambers et al., 2004)

Table 2
Summary of microbiological-related applications and initiatives by location.

Location	Description	References
Africa (several countries)	**1. Water and Sanitation** Project to provide safe drinking water to the population **2. Bioenergy** Use of biogas appliances in Sub-Saharan Africa	(Coca-Cola, 2017) (Tumwesige et al., 2014)
Bangladesh	**3. Bioenergy** Biogas production as a source of income for unemployed women	(Chakrabarty et al., 2013)
Denmark	**4. Bioenergy** Implementation of policies to adopt green technologies	(Lund, 2007; Mæng et al., 1999)
England	**5. Public Health** Campaign to raise awareness on the appropriate prescription of antimicrobial drugs in the North East of the country	(Lambert et al., 2007)
India	**6. Food and beverages** • Preparation of ethnic Himalayan fermented beverage (Chyang) • Use of fermented products as functional foods and beverages **7. Water and Sanitation** Clean India (NBA) and Total Sanitation (SBA) Campaigns **8. Bioenergy** Biogas production to improve economy, health and environment	(Ray et al., 2016; Tamang et al., 2012) (Routray et al., 2017) (Surie, 2017)
Indonesia	**9. Food and beverages** Production of Javanese Tempe-bongkrek by fermenting food waste materials	(Nout and Kiers, 2005)
Nepal	**10. Bioenergy** Biogas production to improve economy, health and environment	(Gautam et al., 2009)
Nigeria	**11. Food and beverages** Sustainable development through manufacture of traditional fermented products (Ogi, Garri, Pito and Iru) **12. Water and Sanitation** Imo State Drinking Water Supply and Sanitation Project	(Adesulu and Awojobi, 2014) (Blum et al., 1990)
Portugal	**13. Public Health** Experimental activities in primary school to promote oral health education	(Mafra et al., 2015)
South Africa	**14. Public Health** Prevention and treatment of diarrhoea	(Chola et al., 2015)

empowered to earn a livelihood from these techniques. Fermented food products, which contribute to one-third of the total diet of the world, can be an effective tool to curb hunger, as well as attain sustainable development by providing employment, alleviating poverty and maintaining food security (Adesulu and Awojobi, 2014).

2.2. SDG 2: zero hunger

Poverty and hunger are two interchangeable terms since the former is the main cause of the latter and all hungry people are by definition poor. According to FAO et al. (2015), 793 million people face extreme hunger on a daily basis, out of which 791 million are from the developing nations. Hunger and poverty, therefore, need to be tackled together, which can be achieved through the diversification of food production technologies and a better integration of the food production systems for their enhanced sustainability (Ali and Suleiman, 2016).

An intelligent investment in farms and smaller food production industries can change the present situation of extreme poverty by enhancing the prospects and income of the poor people (Chauvin et al., 2012). Small-scale fisheries, agro-industrialisation and dairy industry development, are some of the niches which need attention since they can contribute to alleviating hunger if effectively executed (Béné et al., 2007; Petraeus, 2013).

For a sustainable developmental approach, microorganisms can be used in agriculture as a green technology. Microbes are capable of improving soil fertility, crop productivity and biocontrol of plant pathogens. In small agricultural input systems, the application of arbuscular mycorrhizal symbiotic fungi, phosphate-solubilizing microorganisms and different microbe-based pathogen control systems present a significant approach for increasing productivity. (Johansson et al., 2004; Khan et al., 2009). Green microorganisms can be used for bio-fertilisation as well as biocontrol, and will not possess any harm to the environment, unlike the chemicals being used in agriculture (Pereg and McMillan, 2015; Richardson and Simpson, 2011).

A global problem like hunger can not only be handled by just increasing the productivity, but also through the improvements making food accessible to general public. The Food and Agriculture Organization (FAO) has highlighted that the world's hunger problem is majorly the result of the inequitable and undemocratic distribution of and the inadequate access to food (Battcock and Azam-Ali, 1998). A lot of raw materials, fruits and vegetables are wasted due to poor food processing or improper storage conditions, since unfavourable climate triggers the spoilage. There are various methods by which food is preserved like canning, freezing, and drying. However, most of them are expensive or possess food safety implications like botulism (caused by *Clostridium botulinum*) in canned foods.

In this context, fermentation technology is a valuable tool that can be used in different approaches to preserving food, thereby eliminating hunger. Fermentation is an economically-viable and green process by which fruits and vegetables can be stored for longer-term consumption (Ross et al., 2002). By employing microbes like *Lactobacillus, Saccharomyces* and *Acetobacter*, some primary and secondary metabolites with wide applications in food preservation are produced (Caplice and Fitzgerald, 1999; Ross et al., 2002). Alternatively, the salvaging of food waste into a nutritional and utilisable form is another microbiological process by which waste food material is converted into edible form. An example is Tempe-bongkrek, which is produced by fermenting coconut and peanut press cake after the oil extraction (Nout and Kiers, 2005). Alternatively, probiotic microbes are known to increase appetite and cravings for specific foods, thus helping overcome malnourishment (Rezzi et al., 2007).

As mentioned in the previous section, food processing also generates income, being one of the most important sources of employment and livelihood for the populations of Africa, Latin America, and Asia (Battcock and Azam-Ali, 1998). Food items like fermented cereal products, fermented milk products and fermented alcoholic drinks are a significant contributor to their economies (Battcock and Azam-Ali, 1998; Marshall and Mejia, 2012). Further boosting this sector will open new opportunities, help the economy, create more jobs and constitute a source of improved livelihood, thereby assisting in mitigating hunger problems and achieving the second goal of the SDGs.

2.3. SDG 3: good health and well-being

Good health starts with good food. A human being deprived of the daily nutritional requirements cannot remain healthy and is more prone to diseases. In this perspective, the aim should not merely be to produce the higher quantities of food but to ensure its quality as well as safety for maintaining the proper well-being of the people consuming it. As discussed in the previous section, preservation of food by fermentation technology can be a valuable tool for ensuring the quality of food and minimising its waste (Ross et al., 2002). Some fermented alcoholic beverages can be rather used as a functional food which prevents cardiovascular ailments, bacterial infections and other medical conditions (Tamang et al., 2012). Furthermore, probiotics have immunomodulatory properties, which improve gut microbiome and increase the bioavailability of nutrients. They alter the functioning and composition of the gut microbiota and boost both immunity and neurobiology (Hemarajata and Versalovic, 2013).

Even when a proper diet is available, chances of health damage are still high in the developing countries owing to the lack of adequate healthcare, unawareness and ignorance. Therefore, the UN aims at targeting all the control points, which are responsible for the occurrence and spread of diseases causing mortalities. The objectives of the third SDG include ensuring maternal health, ending preventable deaths of newborns and epidemics like HIV or tuberculosis, controlling tobacco use, managing pollution-caused deaths and supporting research for prevention and management of communicable and noncommunicable diseases (United Nations Development Program, 2015a; World Health Organization, 2016).

Microbes are central to health and diseases. In addition to pathogenic microbes, commensals have recently been implicated in affecting the host's health by reaching to the distant organs and interfering with the bodily functions (Hibberd, 2013). Therefore, it is important to understand the microbial transcriptome for better protection of the humans from pathogenic species. It is important to maintain the proper gastrointestinal microflora, as it greatly influences the T-helper (Th) cell-mediated immune response. The increase in Th-2-mediated diseases in the recent past is attributed to the reduced exposure of the immune system to microbial antigens during the early development (Guarner et al., 2006).

Microorganisms play a vital role in maternal as well as infant health. It is now evident that the host-microbe interactions influence the immune health and immunological phenotype of a child. Bacterial translocation from the mother to the child programs the neonatal immune system to recognise specific bacterial molecular patterns. This helps the offspring in responding to pathogens and commensals appropriately (Kaplan et al., 2011; Perez et al., 2007). *Bifidobacteria* and *Lactobacilli* constitute two examples of microbes which are important for immune-regulation in humans (Romano-Keeler and Weitkamp, 2015). Furthermore, maternal dietary factors and hygiene highly influence the immune development of the foetus, and prenatal undernutrition can lead to the development of adult diseases like coronary heart illnesses, type 2 diabetes and stroke (Barker, 2004). The occurrence of diseases due to the lack of proper exposure to the microflora during birth and development can be managed by probiotic/prebiotic therapies. They favour systemic and gut-associated immunological responses and are successful in preventing various childhood diseases like diarrhoea, inflammatory bowel disease and gastroenteritis, as well as in improving the overall human health (Kaplan et al., 2011).

Microorganisms can also play a pivotal role in controlling pollution-related diseases and their mortality rate. Bioremediation for decontamination of soil and water is a green and environment-compatible approach that can help in achieving the sustainable development goals. Microbes act by biosorption and bioaccumulation processes for bioremediation of heavy metals and other contaminants from water and soil, as well as degrade hydrocarbons contaminating both the sea and the soil (Das et al., 2011; Zabochnicka-Świątek and Krzywonos, 2014; see section 2.15). The control of pollution using microbes can help in reducing the incidents of pollution-related diseases and contribute in reaching the third SDG.

2.4. SDG 4: quality education

For attaining sustainable development, education is the most powerful vehicle. Therefore, the fourth SDG aims at free primary and secondary schooling, as well as utilising education for sustainable development, by 2030 (United Nations, 2016a). SDG 4 targets to ensure affordable and quality education, increase the number of skilled youth, eliminate the discrepancies in access to education, expand scholarships and increase the number of qualified teachers, especially in developing countries (United Nations, 2016b).

The UN is putting all efforts in ensuring that the coming generation of youth is skilled enough to contribute to green technologies since education for sustainable development is the key goal of SDG4. In today's era, education is incomplete without studying the different roles that microbes play in our daily lives. Measures are already being taken for developing new methods of teaching fermentation technology, food biotechnology, environmental technology and immunology so that the students easily comprehend the current and future use of microbiology and biotechnology for a better livelihood and environment conservation (Simonneaux, 2000).

Since the most crucial sectors like medicine and agrifood industries make an immense use of microorganisms for the production of drugs and food, it becomes imperative that microbes should be central to education and outreach programmes. This will also empower the youth in becoming skilled in microbiological/biotechnological techniques, ultimately generating a source of income for themselves and their families. The issue that is being confronted as of now is the manner by which interpretation of this instructive branch of science can be made to the overall population's comprehension of well-being and sustainable development. An improved education system will help in reducing the risk of being infected by a pathogenic disease (Prokop et al., 2016). The students of today will become educators of tomorrow and will thus help in further raising the awareness and responsibility of the society towards microbes. Reports suggesting the altered daily behaviour of the students who have studied microbiology as a course are already prevailing (Jones et al., 2013). Behavioural changes including perceptions about not touching any microbe-loaded surface are useful in preventing the outbreak and transmission of diseases. Exploratory element investigations have demonstrated an inconspicuous move in the conceptualisation of transmission dangers from the pre-to post-microbiology course in graduate students (Jones et al., 2013). Primary school education has also shown significant improvement in children for maintaining hygiene after learning about microbes (Mafra et al., 2015). Additionally, raising education and awareness about breastfeeding can improve the immune system and disease-fighting ability of the child (O'Sullivan et al., 2015).

Understanding how the natural ecosystem works and learning to live within the limits of this environment are crucial for surviving in the present times. If every student knows how to use renewable sources of energy and how to adopt a zero-waste technology, it will be easier to achieve our goal of the complete use of green technologies. The content of education should be such that students are first made aware about conserving and restoring natural biodiversity for sustainable development (Cortese, 2003). Moreover, it is imperative to educate the students from primary levels and foremostly, organise awareness programs for outreaching the poor people to send their children to school. The new benefits of expanding microbial education will exceed the expenses related to consolidating the education design or the time spent to train the educators for the best ways to teach the course (Barberán et al., 2016).

2.5. SDG 5: gender equality

Women, being half of the population of the world, also hold half of the working potential and account for more than half of the working force in areas such as healthcare (Kaushik and Kapila, 2009). However, gender inequality stagnates the world's progress by limiting the social and economic development of women. Between 2005 and 2016, it has been reported that 19 percent of the women in the age group 15–49 years has faced violence (Volosevych et al., 2014). Other prevalent discriminations currently faced by women include child marriage, unpaid domestic and care works or meagre percentage in higher positions and national parliaments (Ki-moon, 2016).

The United Nations has identified these issues and considers gender equality to be a principal player in the sustainable development of the world. A major setback for the women around the globe is the restricted access to education. Women require information about sexual and reproductive health, and hygiene (United Nations Development Program, 2015b), since inadequate education about sexually transmitted diseases like chlamydia, herpes, gonorrhoea, AIDS and syphilis poses a greater danger of developing them (Dehne and Riedner, 2001). Women also lack the access to the skills and training required for landing into the labour market and, on an average, earn 24 percent less than their male counterparts (United Nations Development Program, 2015b). Empowerment of girls and women is therefore critically required. It has also been observed that more than 60 percent of the working women are employed in informal jobs. This sector has a real effect on the economy, as it grows faster and creates more jobs when compared to the formal employment sector. Women around the globe are needed to be motivated and trained to join such jobs for income generation and empowerment (Ghebregiorgis et al., 2016).

Encouraging the completion of formal education, inspiring women to join higher studies or learn new skills and raising awareness among the women about their rights can contribute to their growth. The world is now recognising the critical role of women in science and technology. Previous studies which have shown the underrepresentation of women in Science, Technology, Engineering, and Mathematics (STEM) has diverted the attention towards the factors that lead to gender-based inequalities that women face in these fields (Penner, 2015). It has been shown that more women are required in STEM field to satisfy the workforce needs. However, a high percentage of women graduating from these fields end up employed in other areas (Xie and Killewald, 2012). This impulses the fact that women are underrepresented in the field of science and technology and parity is required for an equal contribution of women into STEM.

Gender inequality can be managed by promoting women education and making women skilful enough to earn a livelihood, being STEM one the most practical fields that enable women to land a job. Teaching women about methods of manufacturing and preservation of foods and pharmaceutical products, as well as production of fuels, will not only empower them but also contribute immensely in practising green methods for achieving sustainable development (Palanithurai, 2007; Rao, 2005). As discussed in the previous section, education is also central to health and individuals who are aware of microorganisms have been found to be more cautious towards hygiene (Mafra et al., 2015). Promoting education among women will improve the well-being of their children, families, and society (Roudi-Fahimi and Moghadam, 2003).

Unemployed women spend most of their time with their families and doing household chores. The inadequate access to healthcare, food and biological resources leads women to devote more time to certain tasks like collecting fuel, food or medicines and increases inequality. This can be managed by promoting women of the rural areas for agricultural and land management practices. In agriculture, women can be taught the importance of soil microflora, and the use of beneficial microbes like *Burkholderia*, *Pseudomonas, Rhizobium, Trichoderma, Bradyrhizobium,* and *Azospirillium* for improving crop productivities (Pereg and McMillan, 2015).

2.6. SDG 6: clean water and sanitation

Clean water is an essentiality to human life. Although sufficient fresh water is present on the Earth, four percent of the deaths are due to water, sanitation, and hygiene (World Health Organization, 2009). According to the Centers for Disease Control and Prevention (CDC), 780 million people lack access to a proper water source, and 2.5 million people lack improved sanitation (CDC, 2016). Additionally, it has been estimated that one out of four people will suffer from an acute fresh water shortage in the future (United Nations, n.d.).

Sanitation is vital to health since improper sanitation and unclean water result in the spread of diseases like diarrhoea, cholera, neglected tropical diseases, guinea worm disease, colitis, and trachoma (Smits, 2009). For the reduction in childhood mortality, sanitation and hygiene are listed as the most cost-effective interventions. Only hand-washing practices can reduce diarrhoeal deaths in children by 40 percent (United Nations, 2008). The other methods of controlling poor sanitation-related diarrhoea are rotavirus vaccine, zinc and vitamin A supplementation, improved water sources and hygienic disposal of children's stools (Chola et al., 2015)

In maintaining proper sanitation and providing access to clean water, a critical task is to evaluate the microbial load in the water. The regular enumeration of the microorganisms *E. coli, Salmonella, Vibrio,* and *Shigella* can immensely contribute in controlling waterborne diseases (Cabral, 2010). The potential sources, events and hazards that may lead to the outbreak of water-borne diseases should be identified and documented. The characterisation of risk by pathogen exposure, severity and disease burden can be used for understanding the probability of the infection. The potential sources of pathogens including enteric bacteria are municipal sewage and runoff water from agricultural sources. Furthermore, drinking water has also been implicated as an important carrier of waterborne diseases (Cabral, 2010). Improving water quality should be thus emphasised to reduce microbial load and initiatives to make drinking water completely free from the presence of *E. coli* or any thermotolerant coliform bacteria should be taken (World Health Organization, 2011).

Prevention of water-related diseases and sanitation could lead to a saving of $7 billion per year (Hutton and Haller, 2004), and can increase the GDP of developing countries like Pakistan and Ghana, by 8–9% (World Bank, 2008). Some measures potentially leading to achieving the SDG 6 of clean water and sanitization includes community-led total sanitation, community health clubs, awareness about cleanliness and hygiene, use of low-cost approaches of cleaning water systems and sanitization, green technologies for water purification and full involvement of healthcare system (Mara et al., 2010). Microbes are also efficient in cleaning up water. Microbial biofilms, which work by adsorption and flocculation, are used in various water-treating systems. Various processes like activated sludge and trickling filter are cost-effective green technologies utilized for the treatment of municipal wastewater (Wagner et al., 2002).

Furthermore, increased involvement of the population in water supply and sanitation programmes may help in obtaining improved results. In India, nation-wide sanitization programmes like *Nirmal Bharat Abhiyan* (Clean India Campaign—NBA), Total Sanitation Campaign (TSC), and *Swachh Bharat Abhiyan* (Clean India Mission—SBA) reserve 33% membership for women in water and sanitation-related institutions and bodies, thereby addressing gender inequality while ensuring clean water supply (Routray et al., 2017). Similarly, the RAIN project, funded by the Coca-Cola Company, is focused on providing safe drinking water to the African population (Coca-Cola, 2017). The Imo State Drinking Water Supply and Sanitation Project in Nigeria is a similar initiative working on providing an improved water supply to the Nigerian population (Blum et al., 1990).

2.7. SDG 7: affordable and clean energy

In the mid-eighteenth century, the industrial revolution took place and enabled us to outperform the capabilities of animals and human powers. Electricity generation, goods production and transportation, all got simplified. However, noteworthy environmental changes have occurred as a result of the employment of new energy sources (Chu and Majumdar, 2012). Human population is estimated to achieve 9 billion by 2050, thereby increasing the demand for food, water, shelter, goods, electricity and transport. The increased energy consumption will cause additional environmental complications, which calls for another industrial revolution in which sustainable, affordable and green methods and sources of energy production need to be utilized (Lee, 2011). Cleaner production and technical processes are the need of the hour in order to fulfil the energy requirements of the future generations.

Bioenergy is the energy produced from biological raw materials, i.e. the biomass. Bioenergy offers a solution for a sustainable, clean, and green development of the society and is technically and economically feasible (Baños et al., 2011). Recent advances in research and technology have shown that microbial technology can contribute to the production of green energy at greater levels. Fermentation of liquid and solid biomass by the use of microbes produces biogas, which can be utilized for transportation or power and heat generation (REN21, 2010). Utilization of biomass for first-generation biofuel production mainly relies on the fermentation of sugar, which is obtained chiefly from grains (Goldemberg, 2007). However, this evokes a critical debate of food versus fuel. Second-generation fuels utilize lignocellulose instead but are insufficient to meet the global fuel demands (Hannon et al., 2010). In this context, the use of algae as a source of biofuel production offers an excellent solution to these problems. Algae can grow in a wide number of aquatic environments and have the ability to accumulate high levels of oil, in their biomass. *Botryococcus* can store up to 50% of the biomass in the form of long-chain hydrocarbons (Hannon et al., 2010). Algae proliferate and are easy to manipulate genetically. A further advantage is the simultaneous generation of natural co-products. The most popular algae in this context are *Chlorella, Navicula, Pavlova, and Isochrysis*. The major challenges in the utilization of algae as a substrate for biofuel production are their harvest, action, and down streaming (Brown, 2002; Hannon et al., 2010).

Microbes can also be used for generating clean electricity. For instance, *Shewanella oneidensis* and *Geobacter sulfurreducens* can utilize organic matter such as starch or sugar and produce utilisable electricity from it. This shows the futuristic potential of microbes for generating greener and cleaner electricity. However, this energy-saving technology requires research and development for coming into practice (Lal, 2013).

Biofuels done right can prove to be a substantial source of energy that can be produced in significant quantities and mitigate the global fuel problems. Renewable oil production at a rate of 3200 GJ ha-1 yr-1 has been found to be feasible from the photosynthetic microbe *Haematococcus pluvialis,* showing the practicability of replacing "energy crops" by efficient strains of microorganisms. This would eventually mitigate carbon dioxide emissions while proving to an even greener technology (Huntley and Redalje, 2007).

Microbes can also be used for the production of bioenergy by utilising waste products like sewage sludge, municipal solid waste and agricultural waste (Appels et al., 2011), having microorganisms like *Trichoderma, Aspergillus, Penicillium,* and *Clostridium* proven to be highly efficient in this context (Elshahed, 2010). Similar to bioenergy production, the achievement of sustainable development also requires efficiency improvement, energy saving policies and the introduction of the new technologies which can be implemented for its use. As in the case of Denmark, production of bioenergy utilising biomass led the nation into introducing flexible energy technologies and integrated solutions to energy systems by implementing effective framework policies to adopt green technologies (Lund, 2007).

2.8. SDG 8: decent work and economic growth

The SDG8 aims at reducing the rate of unemployment, improving the labour productivity and economic growth. It has been observed that labour productivity slowed to 1.9 percent from 2009 to 2016, depicting an adverse global economy and poorly paid labourers across the world. The unemployment rate was 5.7 percent, with women being mostly unemployed (United Nations, 2017a). The main agenda of SDG8 is to create employment for the vulnerable groups like women, rural people, and low-income and unemployed urban people (United Nations, 2016b).

As described in the previous sections, microbes can be enormously beneficial for creating employment and adopting green technologies. Increasing the infrastructure for research and development, as well as promoting "green microbes", can enable the people to earn a livelihood.

The enhanced production of microbial fermentation-derived antibiotics can allow an economic and sustainable supply of the active pharmaceutical ingredients. Even the toxins produced by marine microbes can be used for human-health and lead to the mitigation of three problems at a time: control of harmful algal bloom, benefitted healthcare and generation of employment. As an illustrative example, the toxin produced by the dinoflagellate

Karlodinium veneficum is already under investigation for its potential uses in human health (Waters et al., 2010).

The production of biofuels like ethanol and biodiesel presents a secure future for the sustainable and environmentally safe replacement of current fuels. In addition to this, the byproducts of the fermentative production of biofuels are also valuable, and the development of efficient processing technologies can be another source of added value generation. An example of this is glycerol, which is currently treated more like a waste product due to the high cost associated with its processing (Yazdani and Gonzalez, 2007).

Green self-employment opportunities like biogas production have already proven to be effective in various parts of the world. In Bangladesh, biogas has been found to be economically viable for unemployed rural women as a green source of income (Chakrabarty et al., 2013). In parts of Nepal and India, the biogas technology has shown to improve the economy, health, environment and energy conservation (Gautam et al., 2009; Surie, 2017).

Further promotion, improvements, investments and policy implementation in these green and sustainable technologies can be a source of income generation and reduce carbon dioxide emissions, as seen in the case of Denmark, where biogas production policy is a major element contributing to the nation's bioenergy concept (Mæng et al., 1999). In Sub-Saharan Africa, the efficiency of biogas stoves, majorly used for cooking purposes, has been found to be low (Tumwesige et al., 2014). These problems need to be rectified, and efficient products are required to be manufactured by using cleaner production technologies in order to gain maximum benefit from green sources of energy.

2.9. SDG 9: industry, innovation and infrastructure

A sustainable industrial growth and innovation are essential for the sustainable development of the world. Both SDG and Addis Ababa Action Agenda aim at promoting micro-, small- and medium-sized enterprises, and generate productive employment by 2030 (United Nations, 2017b).

A wide array of microorganism provides an opportunity to develop such micro- and small-scale industries, create jobs and boost socio-economic development. Successful industrial and research examples include the fresh Tofu production in small-scale industries in Asia (Rossi et al., 2016), wastewater treatment by anaerobic digestion plants (Maragkaki et al., 2017), biogas production plants, microbrewery wastewater treatment by microbial fuel cells (Dannys et al., 2016), chemical products like methanol, butanol, glycerol and citric acid (Clomburg et al., 2017), and fermented food and beverage products like sausages (Talon et al., 2007), and wines (Mills et al., 2008). Microbial products like ethanol, antibiotics, enzymes (e.g. beta-glucosidase), vitamins and amino-acids are already successful at a larger scale (Wendisch et al., 2006). Microbes like *Pseudomonas and Rhizobia* are used as biofertilizers and boost the agro-industrial productivities (Mohammadi and Sohrabi, 2012; Sahoo et al., 2013; Vessey, 2003), while genetically modified *E. coli* is used for producing large quantities of insulin, which is supporting the high volume of diabetic patients and ensuring their safety (Swartz, 2001).

The persistent requirement of adoption of green technologies, being microbes a sustainable choice, can help us in achieving the SDG9 only if they are intelligently used, widely promoted and effectively implemented. It is also imperative to use only the appropriate starter cultures, especially in the small-scale industries dealing with fermented foods and beverages. Studies have shown that there are certain critical control points which need to be observed and HACCP is to be implemented to maintain the safety of the product use (Holzapfel, 2002). This becomes even necessary particularly in the developing countries, where the mode of preservation and refrigeration are not adequate (Motarjemi, 2002; Sanni, 1993).

The adaptation and efficient transfer of the technology, the building of the infrastructure and the enhancement of the institutional capacity for further research and development of improved strategies and technologies regarding setting-up of small-scale industries are required (Rolle and Satin, 2002). Therefore, not only the production but also a proper control of the processes involved is needed. Infrastructure should be developed to build the industries and to achieve an efficient, safe, green and sustainable productivity.

2.10. SDG 10: reduced inequality

For a successful and sustainable development of the world, it is necessary that the inequalities within and among different nations must vanish. Therefore, equality among nations is a set goal for SDG10 (United Nations, 2017c). This can be achieved by eliminating poverty in the developing and under-developing countries so that they become developed enough to participate equally in the financial and environmental decisions taken at the international platforms.

In the period between 1999 and 2010, income inequality has been found to rise by 11 percent. It has also been reported that more than 75 percent of the population of developing nations live in an area where income is unequally distributed (United Nations, 2017c). Despite the increase in the economy of some countries, the development has not been inclusive. Reducing these disparities and a particular focus on the upliftment of women is the need of the hour. Policies need to be formed for providing an equal employment opportunity, healthcare and other necessities of the marginalized and disadvantaged people.

Increasing the infrastructure for research and development will also help in reducing the inequalities within the nations. Science, technology and innovation are core to the socio-economic evolution of the society. Promoting science can be immensely beneficial for the society, since it is directly linked to health and improvements in this field will help in mitigating the outbreak of diseases.

Moreover, research in the field of sustainability science is highly collaborative and can remove the restriction barrier of underdeveloped countries (Elsevier Research and SciDevNet, 2015). Exchange of students, researchers, and scientists can boost the science status and international stand of these nations. Microbiology and biotechnology are central to health and food, and present a broad scope of research in the field of sustainable science. Improvement in food quality, quantity, control of infectious diseases and large-scale production of quality antibiotics are some of the urgent needs for a sustainable development of the world, and microbes can help in achieving them.

Further, globalization is essential for providing a standard healthcare to everyone in the world. Improving international trades can boost the economy of the developing and underdeveloped nations and provide a source of income for the local people as well (Braun and Díaz-Bonilla, 2008; Díaz-Bonilla and Ron, 2010).

2.11. SDG 11: sustainable cities and communities

With the rapid urbanisation of society, the environment has been drastically affected. In 2015, an estimated 54 percent of the population lived in cities. With an increase in the population, even more basic services and infrastructures will be required, which will lead to an increase in the number of slum dwellers, air pollution and unplanned urban sprawl. These situations will make the world more prone to disasters. Moreover, from 2000 to 2015, the growth of urban cities outpaced the growth of the urban population, showing the pace at which cities are being developed and the environment is being affected (United Nations, 2017d).

Microbes play a significant role in the ecology of urban cities, which harbour a diverse population of transient and resident microbes playing important roles in water management, health and disease, and the degradation of culturally valuable buildings and artefacts (King, 2014). A foremost requisite for the resilient and sustainable development of society is a proper solid waste disposal system to prevent clogged pipes, floods and spread of the waterborne diseases. The disposal of organic waste is a costly process, spending the United States alone around 1 billion USD yearly for this purpose (Lee, 2016).

An efficient, green and sustainable way of solid waste management is its bioconversion to useful products like biofuel, biogas and animal feedstock, as well as its agricultural uses. Composting of the solid waste is an economically viable process that uses microorganisms like *Pseudomonas, Bacillus, Microbispora, Actinobifida,* and *Thermoactinomycetes* for converting its organic constituents into useful end products. Compost can be used as manure for crops, thereby improving their productivity and contributing to green development (Finstein and Morris, 1975).

Municipal solid waste is also converted into ethanol for its use as biofuel (Li et al., 2007; Shi et al., 2009). The waste can be transformed into glucose, which is eventually fermented into ethanol (Shi et al., 2009). This is a critical approach to tackling solid waste, as it produces energy that can curb the depletion of fossil fuels and simultaneously manage the persistent problem of accumulating municipal solid waste in the environment. These bioprocesses can be used if various components including their advantages to soil-plant frameworks, waste collection and proper treatment systems are established (Shiralipour et al., 1992).

2.12. *SDG 12: responsible consumption and production*

The sectoral and national plans require the complete integration of sustainable consumption and production frameworks. This includes green practices, responsible consumer behaviour, sustainable products and services, and proper management of dangerous chemicals and wastes (United Nations, 2017e).

Modernization has deteriorated health quality by increasing the levels of pollutants in air, water, and soil. According to World Health Organization (2017c), more than 80 percent of the people residing in urban areas are exposed to pollutants exceeding the set air quality limits. With declining air quality, the chances of heart stroke, lung cancer and respiratory disease have increased manifolds (World Health Organization, 2017d). Depletion of ozone, acid rains, bioaccumulation of chemicals in organisms and pollution of water reserves are additional implications of human interventions for rapid urbanisation (Austin et al., 2002; Balbus et al., 2013). Therefore, availability of fresh and clean water and pollution-free air are the two primary issues being faced by the people in the 21st century (Simonovic, 2002; van Zuylen, 1998). These problems can be mitigated if the society also takes responsibility by joining the government and contributing to the development of a sustainable livelihood. The use of the requirements that are essential, together with the minimised employment of environmentally hazardous or pollution-causing products is required at the end of consumers (United Nations, 2015). Corporate sustainability and social responsibility are the requirements at the part of the public to work ethically and consider the effects of their organisations of the larger environment.

The efficient use of natural resources and the adoption of alternative energy sources is the ultimate call of the SDG12. The decrease in global food waste, its efficient recycling, the strengthening of scientific research for sustainable green practices and technologies, and the rationalisation of inefficient subsidies on fossil fuels are the goals to achieve the target of sustainable development (United Nations, 2015, 2017e). Furthermore, the implementation of responsible and cleaner production technologies incorporating the use of microbes is one of the important ways of achieving SDG12. Microbial products and metabolites like cellulases, ethanol, and Bacterial Cellulose (BC) from *Komagataeibacter xylinus* provide an opportunity to achieve a responsible production by using these green microbial factories. BC can further be utilized for the production of fuel and Li-ion batteries, thereby showing its potential of being a clean production technology (Jang et al., 2017).

Environmental education is a vital component for increasing the responsibility of the consumers towards their practices and behaviours (Hudson, 2001). Trans-disciplinary studies offer an intriguing insight into the same. Considerable resources including teaching staff, and appropriate team management, along with the simpler organization of the study modules, are required to make the students understand the role of different subjects for achieving sustainable development (Capozzi et al., 2012). Due to the ignorance of humans particularly towards microorganisms, the understanding of their importance in ecological systems and their roles in food and healthcare is under-estimated. The omnipresence of microorganisms, their roles in ecological cycles, their contribution in the production of various antibiotics and increased crop productivities, their scope of being an alternate source of fossil fuels and their bioremediating properties make it a need of the hour to raise awareness about these highly efficient organisms. As microbes are central to biogenic greenhouse gases like carbon dioxide, nitrous oxide and methane, it is of utmost importance to study and understand their roles completely and act in accordance for making their full use to mitigate climate change (Singh et al., 2010).

For all this, microbial education must begin during early schooling and continue to the advanced levels. General public awareness is also much required to raise a sense of responsibility towards a sustainable environment and understand how microbes can help us in this endeavour (Barberán et al., 2016). Seminars and training for using good microbes in food and agriculture can promote green technology and also inspire the general public to build businesses using microorganisms. Maintaining personal hygiene, keeping cleanliness, restricting self-medications, separating organic and inorganic household waste, and minimising the use of fossil fuels can help them and, at the same time, increase the sense of responsibility of the citizens towards the society, thereby promoting sustainable consumption.

2.13. *SDG 13: climate action*

As discussed in the previous sections, microorganisms are central to various biogeochemical cycles of greenhouse gases like carbon dioxide, methane and nitrous oxide. These gases, released by various human interventions and processes like the burning of the fossil fuels and industrial production processes, are the chief players of global climate change and its impacts. An overall increase of almost 2 °C from pre-industrial levels has been observed (Tanaka et al., 2017), which has been mainly accounted for the increase in the emission of greenhouse gases. The SDG13, therefore, aims at urgent actions to mitigate climate change and its effects, to sustain the ecosystem functioning (United Nations, 2017f).

Microorganisms play vital roles in the recycling of elements by interacting with various biotic and abiotic factors. They are fundamental to many natural and engineered systems like wastewater treatment, agriculture, remediation, biofuel production, organic matter breakdown and mineralisation, and production of metabolites (Bodelier, 2011).

Altered global changes including temperature, precipitation and carbon dioxide concentration may be modified due to the response of microbial communities, as they play a role in processes like respiration and denitrification. Moreover, a change in global conditions fundamentally alters the microbial structure of the ecosystem, leading to the formation of a cycle that worsens the situation (Castro et al., 2010; Singh et al., 2010). The soil acts a sink for atmospheric carbon levels due to the activity of microbes, being the process largely affected by a small alteration in soil microbiota (Gougoulias et al., 2014).

There is a high percentage of organic carbon present in the soil as compared to that in the atmosphere and vegetation (Linden, 2007; Smith, 2008). It is therefore imperative to understand the function and ecology of soil microorganisms to increase carbon sequestration. As most of them are still not culturable, this is a challenge in itself. Rapidly-developing technologies like high-throughput screenings are required in this context to fully understand the soil microbial diversity and the prospects of using it in mitigating climate change (Singh et al., 2010).

Furthermore, as a major portion of methane is released by microorganisms, controlling or manipulating microbial communities to quench the increased methane release can be a solution for increasing levels of this greenhouse gas. This can be achieved through improved land use and management techniques or the use of methanogenesis inhibitors like ammonium sulphate (Neue, 1997; Singh et al., 2010).

Applications of nitrogenous fertilizers are highly accountable for the release of nitrous oxide emission in the environment. The adequate use of nitrification inhibitors, reduction of fertilizer use and improved land drainage are some well-established strategies that might help in reducing the proportion of anaerobic environment, which aids in the release of nitrous oxide by microorganisms (Singh et al., 2010; Smith, 2008).

Burning of fossil-fuels, being the most significant contributor to the global climate change, can also be managed by using microorganisms as a source of biofuels or as a part of the biofuel production technology. As previously described, the use of algae for third-generation biofuel production, or that of lignocellulosic materials to convert their sugars into ethanol with the help of microbes like *Saccharomyces* or modified *E. coli,* present a practical, economically-feasible, and achievable solution for the development of sustainable environment (Singh et al., 2010). The use of these green microbial communities may help us in mitigating the global problem of climate change, as well as reducing its impacts on the ecosystem.

2.14. SDG 14: life below water

Seas and oceans are the cradles of life, constituting a necessary resource and a critical component of the Earth's ecosystem which is vital to sustainable development. Due to the increase in population, there has been a rise in the demand for marine resources as well (Eriksson et al., 2015). The overexploitation of these marine resources has caused highly productive fisheries to collapse, and changes in the global climate have exerted their effect on the marine life. More than 141 million tons of fishes are produced annually by wild-capture fishing and aquaculture, out of which oceans contribute 90 percent of the former. Overfishing has reduced food production and has significantly harmed the ecosystem. These situations have led to an urgency of adopting green and sustainable practices with regard to oceanic activities (Srinivasan et al., 2010; United Nations, 2017g).

Also, due to increased dumping of waste into the water, its quality has deteriorated and eutrophication has elevated. This has also caused an increase in the acidity of the ocean water, which has led to the weakening of the shells and skeleton of various marine organisms. Furthermore, the global climate change also increases cyanobacteria blooms in water bodies, leading to eutrophication. Research has shown that increase in the atmospheric concentration of the greenhouse gas carbon dioxide intensifies the growth of cyanobacteria in water, which may also lead to genetic shift (Visser et al., 2016). However, the blue-green algae offer a reliable alternative to the food security of the future generations. These organisms are easy to produce, can even utilize polluted water for their growth, have high biomass yield, and may be used for the manufacturing of an array of products. They can be employed for enhancing soil fertility and arresting the emission of greenhouse gases, thus contributing to a sustainable future (Singh et al., 2016).

Marine microorganisms are also projected to be a future source of various products like biofuels (Peralta-Yahya and Keasling, 2010; Song et al., 2015) and antibiotics (Fischbach, 2009; Nikapitiya, 2012). Algae have also been found to be a potent adsorbing agent which can be used for remediating water-bodies. Conventional treatments like flocculation and filtration are expensive. In turn, algae-like *Nostoc, Chlorella,* and *Azolla,* open the door of a green and economically-viable source of bio-remediation that can afterwards be used for the production of biofuels. So, their utilization targets two aims at one point, being one the restoration of water quality and the other the production of cleaner energy (Gaspard and Ncibi, 2013). Toxic compounds from oil refineries, sugar and paper mills, distilleries, breweries and pharmaceutical industries have been found to be effectively treated by cyanobacteria, showing the tremendous potential these microorganisms hold (Singh et al., 2016). Apart from algae, microbes like *Bacillus, Streptomyces, E.coli, Pseudomonas* and *Marinobacter* can help in remediating heavy metals like lead, arsenic and mercury from marine bodies, as well as assist in controlling marine pollution (Marques, 2016; Naik and Dubey, 2017).

Not only this, microbial communities, being an integral part of the marine ecosystems, are also responsible for nutrient cycling and constitute a food source for higher organisms. Viruses, bacteria, and algae are the dynamic players of the microbial ecology of the oceans. Viruses control bacterial bloom and change their genetic compositions, thereby significantly affecting the ocean health (Bergh et al., 1989; Fuhrman, 2000).

Furthermore, the use of microbes in aquaculture can effectively boost the production of fisheries by controlling the pathogenic outburst and water quality, as well as regulating the environmental impact. Formulation feed is the most-expensive operational cost in fish and crustacean aquaculture, and thus can be alternated by using microbial flocs as a source of nutrition, which has been highlighted as a green, economically-feasible and most sustainable futuristic approach to mitigate food shortage that can bring about the next green revolution in food production (Martínez-Córdova et al., 2016).

Thus, microbes can be used in mitigating the pollution of marine bodies, as a source of nutrition in aquaculture and as an alternate source of human food, thereby constituting a substantial means of achieving the SDG 14 and providing a better life to marine organisms if used appropriately.

2.15. SDG 15: life on land

With an increase in the population of human beings, the requirement of land for their habitat has also increased owing to the destruction of forests and loss of land biodiversity. It has been estimated that from 1900 to 2015, the world's forest area declined from 31.6 to 30.6 percent (United Nations, 2017h). The infrastructure development and agriculture have been implicated as the two main reasons for this process.

The loss of animal and plant biodiversity has become a topic of debate in the last decades. Less has been spoken, however, about the loss of invisible organisms: the microorganisms of the soil. There are over ten million microbes in 1 g of soil, constituting these an essential part of the food web and biogeochemical cycles. They stabilize the soil structure, enable nutrient uptake by plants, control pests and diseases, decompose organic material and degrade harmful chemicals, as well as being an indicator of the soil health (Wachira et al., 2014). Because of their high surface to volume ratio, they have an intimate relationship with their habitats and any change in the soil ecosystem is sensed by them, triggering a quick response in their diversity (Nielsen and Winding, 2002). For instance, the altered carbon and nitrogen levels in the soil during wet seasons lead to changes in microbial communities (Pajares et al., 2016).

Deterioration in the soil health directly affects all life forms, as groundwater, surface water and air all are adversely affected by an unhealthy soil structure. Microbes, being the key players in regulating the nitrogen, phosphorous and sulfur levels, as well as the decomposition of decaying organic matter, are essential for maintaining the health of the soil. They immobilize minerals, which become available to the higher organisms that feed upon them. Furthermore, microbes also degrade the chemicals that are added to the soil due to agricultural, industrial and construction practices (Nielsen and Winding, 2002).

Microbes are crucial to agricultural practices through the regulation of the biogeochemical cycles. They play a role in soil fertility by providing the crops with carbon, nitrogen, and phosphorus for their growth and development. They fix nitrogen, solubilize phosphorus, and chelate iron to make these nutrients available to the plants, thereby improving their productivities and minimising the use of hazardous chemical fertilizers that affect soil health and may also accumulate in the food (Wachira et al., 2014). The use of microbes as biofertilizers can improve crop yields and protect the plant from pathogenic invasions (Kumar and Gopal, 2015).

The bioremediation of hazardous chemicals through the use of microorganisms is another green process that can be used to improve soil health and ultimately land life. Microorganisms such as *Burkholderia, arthrobacter, Chromobacterium, Micrococcus, Candida, Pseudomonas, and Bacillus* can degrade crude oil and hydrocarbons, that too without any artificial enhancement, by the process known as intrinsic remediation (Das et al., 2011; Kumar and Gopal, 2015). Effluents from mining and metallurgical areas pollute water and soil systems, thereby affecting both marine and land life. Microbes like *Shewanella*, *Bacillus subtilis* and *Brevundimonas* have been found to remove magnesium, calcium and iron from such polluted waters, proving their efficiency in the bioleaching of metals from contaminated water (Kumar and Gopal, 2015).

Thus, microbes can be used to improve the biodiversity of land-organisms, increase plant biodiversity, enhance food production and control land pollution. Being so efficient and playing deep roles in soil ecosystem, microbes can be a way of achieving the SDG 15 of improving life on land.

2.16. SDG 16: peace, justice and strong institutions

This goal aims at promoting inclusive and peaceful societies for the sustainable development. Violent conflicts have been reported to increase in the last decades, while homicides have decreased (United Nations, 2017i). Prevalence of poverty, inadequate access to food and illiteracy leads to an adverse effect on the development of children (Chilton et al., 2007). Food insecurity has been implicated as a major factor in contributing to the mental well-being of children (Slopen et al., 2010) and it still affects almost 11 percent of the households in the United States (Chilton and Rose, 2009). Poverty and hunger have been linked to social implications (Slopen et al., 2010).

Although microbes do not have a direct link to peace, they may, however, significantly contribute to maintaining a peaceful society. As discussed in the previous sections, microbes can provide a means of earning a livelihood by the small-scale set-ups. Being employed provides a sense of contentment, and young minds are less diverted to violence (Cramer and Group, 2010). In turn, unemployment and problem drinking have been associated with partner violence (Cunradi et al., 2009). This shows that the inability to earn bread causes stress among people and is also a causative factor of non-peaceful societal conditions.

Further, bioterrorism, the use of living organisms (pathogens) or their products (toxins) for harming humanity, has become a major threat, keeping in view the low tolerance of nations towards each other. Nevertheless, microbial forensics can be used as a powerful tool for combating bioterrorism. The combination of traditional investigative approaches and molecular biology techniques can help in tracing the perpetrators and sources of the bio-hazard (Budowle et al., 2005; Sijen, 2015). Unfortunately, microbial forensics is not very well-established discipline, and research and training are required to make the officials adept at utilising these techniques for combating bioterrorism and sustaining peace.

Microbes can help in achieving the SDG 16 by combating bioterrorism, as a source of nutrition, improving environmental conditions, implementing green technology and improving national and international infrastructure that would ultimately lead to the development of society and the prevalence of peace and justice.

2.17. SDG 17: global partnership for sustainable development

Sustainable development is not feasible without an active cooperation and collaboration between nations. Finance, information and communications technology, capacity building, data monitoring and compatibility, and trade are the most important issues that require partnership at a larger scale (United Nations, 2017j).

Capacity building on trade-related aspects of biotechnology is the need of the hour. The benefits of microbes and microbial technology can only reach the masses through globalization and overcoming land barriers. This green technology must be used to reinforce the values of social justice and equity (Chambers et al., 2004).

Policy frameworks are required to make microbiology contribute to the social, economic and environmental needs for achieving sustainable future. The uses of microbes in agriculture, pharmaceutical science, biofuels and fermented foods are the most critical areas which need urgent attention. More internationally open business, flexible policies and exchange of researchers is required between nations. Furthermore, developed countries should support and make the trade easier with developing countries so that everyone gets benefitted and the technologies reach to those who need them most urgently (ICTSD, 2007). Application of wisdom in microbial technology and globalized production for human progress can only be achieved. Regionally important groups like The North American Free Trade Agreement, European Union, South African Development Committee, Association of Southeast Nations, Arab Organization for Agricultural Development and Asia-Pacific Economic Cooperation are already working in the direction of hassle-free and secure trade between the participating nations (DaSilva, 1998). More different, larger, and inter-continental agreements are required to make globalization more productive.

3. Research gaps and Recommendations

3.1. major research gaps and challenges for future research

The present times face an energy crunch, global climatic issues, food insecurity and inadequate supply of potable water along with various other environmental issues. In this context, microbes can significantly contribute to achieving sustainable development and offer cleaner production technologies.

However, for the efficient use of microbes in achieving the sustainable development goals, further research and development are needed. The foremost requirement is to understand the microbial transcriptome completely. A complete database of the microbes present in the environment can help us to comprehend the potential and implications of these microorganisms in various ecological, biotechnological, and industrial processes.

For developing green and cleaner production technologies, advanced scientific studies are required so that microbial products like biofuels become abundant, affordable and accessible to each nation. Depleting natural sources of energy, the primary concern for the sustainable future, have a promising alternative: biofuels. However, research is needed for developing the methods of cost-cutting and use of diverse substrates for converting them into biofuels. Production and enhanced activity of microbial enzymes would immensely contribute to the practical application of the biofuel technology.

Research should also be carried out for a better understanding of microbial pathogenesis, as well as in the development of microbial medicines for combating pathogens. Emerging drug-resistance urges to find newer antimicrobial compounds and drugs that would be able to combat superbugs and related epidemics, both in the developing and developed nations.

Finally, molecular-based studies should be carried out to investigate the advanced use of microbial forensics and bio-detectors for maintaining peace and prosperity in the present and coming era.

3.2. recommendations

To effectively achieve the targets of sustainable development, the most significant steps are required from the governments' end. Governance, legislation, and policies are urgently needed to implement the concepts of sustainable development and sustainability.

Improved funding for research and development, a framework for deploying and boosting the existing green and clean production technologies and improving the infrastructure for education and awareness campaigns, as well as the promotion of microbe-based small and medium scale industries, are the ways that can contribute to achieving the SDGs.

Microbial biotechnology can be an approach to boosting industrial set-ups, raising employment rates and overall GDP of the nations. Promotion of the use of microorganisms as bio-fertilizers can decrease the deterioration in the soil quality and increase crop productivities.

Furthermore, researchers are also suggested to not only emphasise on the health and disease aspect of microbiology, but also on the other significant applications of this science like fermented foods, bio-detectors, microbial electricity, microbes as a source of food and biocontrol agents.

Advanced studies are required in each of these fields and the collaborative efforts of scientists can help in moving towards the practical application of these green technologies and achieving sustainability. Furthermore, regular environmental sustainability assessments are also recommended to evaluate and mitigate the risk of further damage to the global environment.

4. Conclusion

Keeping in view the increasing consumption of non-renewable sources of energy, deteriorating quality of global climate, increasing carbon footprints and prevalent poverty in the world, as well as the means of achieving sustainable development and a cleaner environment, have become an urgent requirement. Although some steps are being taken in this direction, practical measures utilising the microbial resources are still lacking.

In this context, microorganisms can contribute significantly to mitigating climate change, enhancing green production technologies, improving crop productivities and providing a means of earning a livelihood. It is still not too late to take the steps in achieving the goal of cleaner production technologies and sustainable development by using green microbial technologies.

However, despite the promising results of microbial methods, the cost of the industrial set-ups and production methodologies remain a major hindrance in practising microbial technology. The development of cost-effective technologies for implementing microbial production methods can be a breakthrough achievement and may be a step towards the “microbial revolution”, ultimately mitigating the environmental issues.

Nevertheless, this will not be feasible without crossing the country barriers and improving national infrastructures and policies. Greater efforts and collaborations are required on the international scale and the reasonable efforts will generate sustainable results, cleaner production technologies and a balanced and sustainable ecosystem.

Conflicts of interest

The author declares that the review was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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