ADVANCES IN APPLIED MICROBIOLOGY FOR SUSTAINABLE DEVELOPMENT

Neelam Jain[1], G. K.Aseri[2], Jagdip Singh Sohal[2], Deepansh Sharma[2], Vinay Sharma[1], A.N.Pathak[3], Y. V. Singh[4], Joginder Singh[5], Umesh Chandra Pachouri[5], Rahul C Ranveer[6], Vijay Upadhye[3], Era Upadhyay[1], Shweta Kulshreshtha[1], Manishita Das Mukherji[1], Manali Datta[1], Deepti Singh[2], Anupam Jyoti[1], Ravneet Chug[1], Sanket Kaushik[1], Vijay Kumar Srivastava[1], Sudarshan Singh Lakhawat[1], Sunil Kumar[1], Vigi Chaudhary[1], Neeraj Khare[2], Parul Yadav[7], Kingsley Oyediran Oke[8], Olubunmi Peter Ojo[8], Samuel Olusegun Oyewumi[9], Vishal Saxena[10], Simranjeet Singh[11], Manoj Kumar[12], Veerendra Nagoria[13], Pradeep Kumar Singh[13], Lalit Kumar Singh[14], Dignya Desai[1], Vishakha Sharma[2], Rajbala Junia[2], Ekta Narwal[4], Kanika Bhargava[2], Neha Singh[2], Pradeep Kumar Algar[2], Mehak Manzoor[2], Gulshan Sharma[1], Jyoti Yadav[1], Mrinalini Roy[1], P. Chaitanya[1], Pooja Sharma[1], Smriti Yadav[2], Keya Patel[2], Rasanpreet Kaur[2], Vikrant Sharma[2], Muddapuram Deeksha Goud[1], Rishab Singh Jauhari[1], Bharti Singh Jadoun[1], AsmitaSingh[1], Pallavi Kachhawah[3] , Mohit Thorecha[1], Akshata Mandloi[1], Rajal Patel[1], Krati Khandelwal[1], Nishtha Gaur[1], Shweena Krishnani[2], Esha Dwivedi[14], Deepanshu Sharma[1]

[1]Amity Institute of Biotechnology, Amity University Rajasthan, NH-11C, Kant-Kalwar, Jaipur
[2]Amity Institute of Microbial Technology, Amity University Rajasthan, NH-11C, Kant-Kalwar, Jaipur
[3]Centre of Research for Development, Parul University, Waghotia, Vadodra, Gujrat, India
[4]Division of Microbiology, ICAR-Indian Agricultural Research Institute
[5]Department of Biotechnology, Lovely Professional University, Phagwara, Punjab, India
[6]Postgraduate Institute for Post-Harvest Management,

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Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth,
Ratnagiri,Maharashtra- India
[7]AUSIC, Amity University Rajasthan, NH-11C,
Kant-Kalwar, Jaipur
[8]Department of Biology, Emmanuel Alayande College of Education,
Oyo, Oyo State, Nigeria
[9]Department of Agricultural Education, Emmanuel Alayande
College of Education, Oyo, Oyo State, Nigeria
[10]Department of Biological Sciences, NSB, Molecular Parasitology
& Systems Biology Lab, Birla Institute of Technology & Science,
Pilani – 333031,Rajasthan, India
[11]Interdisciplinary Centre for Water Research (ICWaR), Indian
Institute of Sciences, Bangalore, India
[12]Department of Life Sciences, Central University Jharkhand,
Brambe, Ranchi, Jharkhand, India
[13]School of Life Sciences, Rai University, Ahmedabad, Gujarat
[14]Department of Biochemical Engineering, School of Chemical
Technology Harcourt Butler Technical University Kanpur-
208001(U.P.) India

Introduction

"The role of the infinitely small in nature is infinitely great…". The prevailing global pandemic Covid-19 reminds us of this quote by the Father of Microbiology-Louis Pasteur. The current pandemic makes us realize and reimagine the immense power of the tiniest microorganisms to impact the entire world making humanity helpless. The ubiquity of the microorganisms throughout the biosphere and the diversity of their activities and their metabolites make microbes pivotal agents of planetary and ecosystem functioning since the dawn of civilization.We have entered the Anthropocene, a new geological epoch when humanity's influence is instigating global climate change and also disrupting the relationships between microbes and their hosts that have been living together for millions of years.

Although microbial technologies broadened in range over time yet a quantum increase was observed due to the technological advancement through metagenomics, proteomics, and transcriptomics. The applied microbiology focuses on the wide spectrum application of microbes in the production of animal and plant based food and supplements, regulation of biogeochemical cycles, maintaining the soil structure and fertility, the generation of energy, chemicals and biomaterials through fermentation, management of pollutants and waste, bioremediation, production of vaccines, novel drugs, diagnostic tools, and biosensors, microbial therapies for combating diseases, and the genetic and protein engineering. The microbes are also vital determinants of climate change and ecosystem productivity. Microbiology is an evolving field and is advancing with the advent of newer techniques and analytical procedures, new horizons in instrumentation and miniaturization, and increasing application of systems and synthetic biology for sustainable development.

Microbes in Sustainable Agriculture

The global rise in food demand and efforts to feed the escalating population with the introduction of new crop varieties and agrochemicals have considerably disturbed the global ecosystems.

Microbial inoculants serve as a suitable approach for sustainable agricultural development and ensuring food security in changing climate without compromising environmental health.They can be successfully used as biofertilizers and biopesticides to enhance nutrient uptake, promote crop growth, or protect plants from pests and diseases.They are commonly classified based on inoculant composition and functional interactions with plants as nitrogen-fixing biofertilizers, solubilizing and mobilizing biofertilizers, micro-nutrient biofertilizers, and growth-promoting biofertilizers. Most commercial biofertilizers are transformed into bioformulations of individual or consortium of bacteria, fungi, blue-green algae (BGA).

Biofertilizers also serve as efficient agronomic tools for modulating environmental stresses like drought, salinity, heat, cold, and heavy metals, etc. and enhance productivity in many agro-systems. These microbes may also affect ecology and soil microbial community structure thus leading to improved soil health status. The use of integrated nutrient management and involvement of microbial inoculants as per the soil health profile is recommended for sustainable agricultural development.

Microbial Inoculants for Bioremediation

Increasing urbanization and industrialization have exerted an alarming impact on the human health as well as the ecosystem functioning by aggravating the environmental pollution. The release of heavy metals, dyes,polycyclic aromatic hydrocarbons and other hazardous organic and inorganic pollutants through industrial effluents in water bodies is a matter of serious concern as it can impact both the water and soil quality, and are carcinogenic and toxic at even low concentrations. They can lead to biomagnification and bioaccumulation at various trophic levels, eventually reaching humans where they can be fatal. Bioremediation is a successful green technology option to tackle the menace of these hazardous pollutants and an aggressive approach for environmental clean-up utilizing the intrinsic capability of microbes and plant biomolecules. The microbes from different genera of rhizobacteria, endophytes, and fungi, and even

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genetically engineered microbes have been identified for their ability to degrade organic pollutants and detoxify heavy metals, pesticides, azodyes, and polyaromatic hydrocarbons, through biotransformations.

Phytoremediation is also a competent, environmentally friendly, and cost-effective approach for the detoxification of pollutants from contaminated soil or water through the application of plants. *In vitro* hairy roots can be developed in certain plants through infection with *Agrobacterium rhizogenes*, a natural genetic engineer. Besides this, the rhizospheric microorganisms living close to these hairy roots also enhance the tolerance against the lethal chemicals.

The relationship between soil microbial communities and climate change is very convoluted. Soil microbes are also known as 'environmental modulators' that impacts organism activity but frequently alters through their influence on resources. Climate change can affect directly or indirectly soil microbes which play a prominent role inrecycling nutrients through biogeochemical cycles and controlling plant population for terrestrial ecosystem sustainability.

Waste management is the upcoming challenge especially for the developing countries in which microorganisms can play a vital role in providing sustainable solutions and pave the path for healthy environment. Management of agricultural farm wastes like 'Parali/Stubble' through consortia of microbes recently is a classic example to show involvement of the microbes for sustainable agriculture.

Microbes in Food Production and Food Safety

The association of microbes, the human microbiome, diet, and food safety has played a critical role in the development of the modern food industry. Microbes have been used in the production, preservation, and fermentation of food and beverages since the dawn of civilization. Microbes play a very crucial role in processing animal-based food products through their enzymes increasing their nutritive value. Mostly these include fermented foods like Yogurt, cheese, Kefir, sweet chocolates and silage, etc. Bacteria like Lactic acid bacteria and Bifidobacteria are being used in the food industry as probiotics which help in curing diseases of digestive systems and intestinal disorders. The lack of a vaccine or curative treatment for Covid-19 necessitates a focus on other strategies to prevent and treat the infection. Probiotics can reduce the incidence and severity of diseases by strengthening immunity, suggesting their promise for treating or preventing COVID-19.

Even many algae-like *Spirullina* are used as a source of single-cell protein. Fungus like a mushroom is already consumed as a nutritional as well as a therapeutic food. Yeast and other fungus plays a phenomenal role in the food industry today. Yeast, including *Saccharomyces cerevisiae,* is used in baking as well as in the fermentation of alcoholic beverages. Yeast species have both therapeutic properties as well as probiotic potential.Yeasts have several health benefits including antioxidant activities. In the recent decade, modern research based on the development of functional foods and nutraceuticals with the help of yeast has shown robust potential in food biotechnology.

Food safety and its quality have become the overriding preoccupation for food processing industries in the current scenario. The statistical data of the Food and Agriculture Organization (FAO) indicates that approximately one-third of the total food produced is lost or wasted every year due to inadequate storage facilities, improper preservation, spoilage, or deterioration caused by microbial activity. The chemical preservatives used in food industries may be hazardous to humans in long term use. Therefore food preservation by using natural antimicrobial compounds like bacteriocins from Lactic acid bacteria could be an alternative to chemical additives.Bacteriocins can also used be as an effective biocontrol agent and edible biopolymeric film in food processing industries.

Biomedical Applications of Microbes and AMR

Bacteria are among the most malleable organisms on Earth. The widespread use of antibiotics has resulted in Anti-Microbial Resistance (AMR)which is currently the greatest challenge to the effective treatment of infections globally. Thus efforts are being made to discover novel antimicrobial products of natural and synthetic nature to tackle the menace of AMR.Therefore, researchers focus has turned to a century-old antimicrobial method popularly known as phage therapy in fighting against AMR which uses Bacteriophages, natural predators of bacteria to suppress their infections. Even the plants derived drugs have recently received more attention as an alternative to antibiotics due to their high efficacy and lesser side effects. Microorganisms are used in the production of vaccines, insulin, serum antibodies, and essential hormones. Advancement in disease diagnostics with the development of technology has resulted in the early detection of pathogenic microorganisms. Exploration of microbiomes with respect to their influence on host immune system, nutrition, and disease is accelerating the progression of novel microbiome therapy for disease treatment and prevention.

The occurrence of multidrug resistance (MDR) and extensive drug resistance (XDR) have prompted medical fraternity to seek alternative drug targets and new ligand design strategies such as structural based drug design. The rational structure-based drug design works on the understanding of three-dimensional structures of biological targets to discover novel drugs.

Biosurfactants are the secondary metabolites derived from microbes posessing potent antimicrobial, antifungal, and antitumor properties besides their anti-adhesive nature against various pathogens for application in the health care sectors. Biosurfactants being natural, andsustainable with low cytotoxicity, has thus gained prominence in dealing with the current pandemic of Covid-19.

Microbial Intervenetions in Industries

Industrial microbiology aims to discover new microorganisms, pathways, and metabolites for the benefit of mankind. It is the application of scientific and engineering principles to the processing of materials by microbes and their enzymes. Microorganisms have great potential to facilitate the production of chemicals, pharmaceuticals, and food-grade products. The array of polysaccharides, polyamides, polyesters, biopolymers, organic acids and, bioplastics, etc.are produced by wild as well as genetically mutated strains of microorganisms having widespread medical and other industrial applications. Now-a-days, even cosmetic industry has also open doors for microbial products where Botox is already in use and many more are on the way.

Microbes and their enzymes have immense potential in handmade paper and leather industries in bio-pulping and bio-bleaching, leather processing of fibers in an eco-friendly manner. Further, waste can be treated by using different fungi, mushrooms, and anaerobic digestion techniques. The microbial food grade coloring agents derived from bacteria and fungi are natural, cost effective, easily degradable and without producing recalcitrant intermediates when they enter the ecosystem.

Microbes for Bioethanol Production

As there is a rapid growth in population and industrialization, the overall ethanol demand is increasing persistently. Conventional crops like corn and sugarcane are not able to fulfill the global demand for bioethanol production due to their primary value of food and feed. Therefore, lignocellulosic biomass like agricultural waste residue and newspaper biomass are more appealing feedstocks for bioethanol production. *Saccharomyces cerevisiae* is the most employed organism for ethanol fermentation. The conversion of non-fermentable substances into compounds for improving the alcoholic fermentation can be achieved with the addition of some commercial enzymatic complex of amylases, cellulases, and amylo-pectinases.

Microbial Enzyme Engineering

Enzymes having the capability of bioconversion have always been at the center of research for sustainable development. Microbial enzymes as a metabolic catalyst have been crucial in the development of various industries as they are sustainable and efficient. It has been reported that microbial enzymes are currently being used to produce more than 500 industrial products. Protein engineering by modifying existing gene sequence or through synthetic gene sequence is a promising technique for the design and development of proteins with the desired properties. Protein engineering can be looked for providing solutions to modern-day industrial problems either by redesigning the approach or by denovo synthesis.

Microbial Fuel Cells

The world is facing a global power crisis currently due to huge energy demands and limited resources. Today the world is looking for alternative sustainable solutions for the production of energy since the increasing use of non-renewable fossil fuels led to climate change and environmental pollution. So, Microbial Fuel Cell (MFC) can serve as future biofuel that can generate electricity and can even treat wastewater. MFC are bio-electrochemical devices, for harvesting sustainable energy using microorganisms that convert the chemical energy of organic matter of waste into electricity. The world now has a greater responsibility to adopt these sustainable measures, cleaner production, and green technologies so that the natural resources of the Earth may be conserved for future generations.

Microbial Biosensors

Microbes can be easily engineered and streamlined with unprecedented capabilities for disease diagnosis, detectionof spoilages and environmental contaminants. A microbial biosensor is an analytical device that integrates micro organism(s) with a physical transducer to generate a measurable signal proportional to the concentration of analytes. The ability to detect disease early and deliver precision therapy would be transformative for the treatment of human illnesses. Moreover, assessing food quality for the microbial presence and thus its safety and palatability using standard microbiological methods had become a major hurdle for the food industry and public health. The development of microbial enzyme-based sensors has enhanced the effectiveness and specificity of the detection of harmful bacteria in food samples.With an era of converging technologies, new diagnostic platforms for assessing food quality have been developed by incorporation of Nanotechnology inclusive of nanomaterials with unique electrical and photonic properties, as well as biomaterials with high biocompatibility are the most effective strategies for developing biosensors with an ultrafast response.

Conclusion:

Modernization has thrown humanity into a ditch of self-created problems, which require utmost attention and solutions to come out of it. The current global scenario displays energy crisis, depletion of natural resources, increasing carbon footprints, lack of potable water, climate change issues, economic as well as food and health crisis around the world. In this context, microbes can significantly contribute to achieve sustainable and affordable solutions for the development of cleaner production technologies to mitigate climate change issues, enhance crop yield, tackle health emergencies due to infectious pathogens and AMR. The Covid-19 pandemic taught us a lesson to handle the microbes with utmost care, hence the judicious use of microorganisms is essential to get maximum economic, social, and environmental benefits. Despite a spectacular advancement of applied microbiological research from classical to modern techniques,more than ninety percent of microbial diversity still remains to be revealed. Exploring this gold mine of unmapped microbial diversity using novel tools and techniques will open new avenues in the microbiological research for sustainable development of our ecosystem.