SUSTAINABILITY SCIENCE

(Multidisciplinary Approaches to Global Challenges)



Editors

Dr. Monita Dhiman

Dr. Mishu Gupta

VYOM HANS PUBLICATIONS

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Sustainability Science

Multidisciplinary approaches to global challenges

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PREFACE

In an era marked by complex global environmental challenges, the pursuit of sustainability is no longer optional; it is an urgent and universal imperative. The growing threat of climate change, the rapid depletion of natural resources, increasing pollution, and persistent socioeconomic inequalities demand a shift in our scientific, policy, and educational frameworks. It is in response to this compelling need that the present volume, *Sustainability Science (Multidisciplinary Approaches to Global Challenges)*, has been envisioned and curated.

This book brings together a diverse collection of 19 chapters contributed by academics and researchers, each offering unique perspectives into sustainability. The topics span a wide range of interconnected domains, environmental education, green technologies, biodiversity conservation, renewable energy, sustainable agriculture, climate politics, public health, and the transformative potential of artificial intelligence and nanotechnology. Together, these chapters underscore the necessity of cross-disciplinary collaboration in addressing 21st-century sustainability challenges.

A distinguishing feature of this volume is its inclusive approach to sustainability science. From exploring India's journey toward achieving the UN Sustainable Development Goals to case-based interventions on crop residue management, eco-packaging, and climate-resilient farming, the book integrates macro-level policy reflections with grassroots-level practices. It encourages the reader to appreciate the interconnectedness of human well-being, ecological integrity, and technological innovation.

We express our deep gratitude to all the authors whose insightful contributions shape this publication. We hope this book inspires reflection, dialogue, and action. May it serve as a catalyst for integrating sustainability into curricula, research, and policy and above all, into everyday consciousness.

Editors

CHAPTER- 01

ENVIRONMENTAL EDUCATION AND AWARENESS

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Abstract

The phenomenon known as "Environmental Education and Awareness" includes sensitivity of individuals, development of social groups and understanding of issues of environment as a whole. The study of importance and implementation of environmental education and awareness are crucial as environment is changeable phenomena and its study can't be determined for a longer time. The significant environmental challenges such as climate change, pollution, deforestation, loss of biodiversity influences the Demographic and economic aspects also. Environmental education and awareness is about shaping behavior and attitudes towards the environment. The implementation of environmental education gives way to the awareness regarding its issues among students. Environmental Education and Awareness helps in maintaining the understanding between human activities and natural systems. It's a comprehensive approach which helps the students in the recognition of urgency of environmental issues and the need for sustainable development. The most important aim of environmental education is to create a sense of responsibility towards the surrounding, by developing understanding of causes and effects of environmental degradation among students. It encourages the students to adopt and to promote sustainable lifestyles. Environmentally aware youth has the potential for the long time protection of changeable environment. Environment Education and Awareness enables the youth to rise a great voice on environmental issues. The impact of education on environmental awareness results good influence on social norms and values, solution of environmental challenges,

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achievement of sustainable development goals, promotion of contribution towards environmental conservation and sustainability. This comprehensive study includes educational strategies with which we can achieve a healthy environment required to solve the environmental issues of our time with insurance of sustainable future.

Keywords: Awareness, Climate Change, Deforestation, Environmental Degradation, Education.

Introduction

Today environmental education alongside awareness maintenance represents a vital foundation for our global society. Environmental understanding with its associated challenges of climate change and deforestation and pollution and biodiversity loss has become vitally essential as we enter this new millennium. Environmental education works to teach individuals necessary knowledge and develop both skills and attitudes for protecting natural world resources. Fresh environmental education creates responsible minds which support strict conservation measures. People require environmental education because various growing environmental crises create major threats to Earth's well-being. Environmental issues including carbon emissions increase and decreased resource levels combined with waste accumulation need swift solutions. Local people actively play an essential role in environmental sustainability even though worldwide organizations and governments implement different policies to face environmental issues. On Triggered by educational initiatives people can learn to make decisions which simultaneously support environmental preservation and societal welfare (Kumar et al., 2025). The understanding of environmental problems and natural ecosystem protection initiatives makes up environmental awareness. The understanding focuses on how humans connect to nature along with knowing how their everyday habits influence the environment. Sections of education provide knowledge needed to establish sustainable activities which leads communities toward lower impact on nature.

Environmental education and awareness need active engagement between the local communities. Local communities maintain distinctive environmental issues which need specific local remedies. Educational programs that inform community members about environmental issues often produce group actions that create sustainability. Educational awareness efforts regarding clean water together with energy conservation and waste segregation information lead communities to implement sustainable behaviors. (Valderrama et al., 2025)Through modern technologies efforts to spread awareness take place in a manner that lacks aggressiveness. The ongoing growth of technology has helped greatly in raising environmental consciousness among people. People

can now easily acquire and distribute environmental information through internet platforms together with social media and digital tools. Extended multimedia outreach from campaigns through documentaries combined with web-based materials demonstrates substantial power to mobilize action from large number of individuals. Modern technology allows educators to teach environmental concepts through virtual simulations combined with interactive tools which increase student engagement while improving educational effectiveness. A variety of obstacles continue to hinder efforts to improve environmental education along with awareness levels throughout the world. A primary difficulty arises because educational institutions worldwide lack enough trained teachers together with limited funding. A few parts of the world encounter problems because environmental issues remain neglected within academic curriculum and students fail to understand these matters. Environmental progress suffers when people hold incorrect beliefs about environmental problems. Local communities often have unique environmental challenges that require tailored solutions. Educating community members about these issues can lead to collective action, resulting in more sustainable outcomes (Nogueiro et al., 2025)

The learning tools are able to make learners take responsible decisions regarding waste management, resource consumption, energy conservation, and sustainable agriculture. Awareness plays a crucial role in determining attitudes towards the environment. It is the first step towards forcing any kind of change. A person who is not aware of environmental problems, such as air and water pollution, destruction, or global warming, is less likely to feel. The individual with global warming will not feel inclined to act on the issue. Environmental awareness campaigns, whether in mass media, digital platforms, or grassroots movements, play a crucial role in informing the public of environmental issues and what actions must be taken to deal with them. Awareness is more than just educating people on the state of the planet but also on how to contribute to its betterment (Mathebula, 2017). By providing concrete actions that individuals can take, such as reducing plastic use, conserving water, supporting renewable energy, and planting trees, environmental awareness Issues such as planting trees can best be addressed through environmental awareness campaigns where issues feel personal and actionable. In addition, environmental awareness can give people a sense of collective responsibility with the freedom to advocate and collaborate with people in order to improve how things are done in society. For example, people informed about single-use plastics' destructive tendencies opt to use reusable bags, bottles, and containers in their activities and lead by example to others (Beak et al.,2023).

Environmental education together with awareness represent fundamental solutions for dealing with environmental challenges during the 21st century. The teaching methods give people essential information paired with necessary skills which lets them make well-informed choices while developing sustainable methods that support planet preservation. The educational approach focuses on developing student responsibility while stimulating immediate environmental action to produce enduring beneficial impacts on social collective harmony. The critical need for educating people about environmental issues will expand with rising worldwide environmental threats. This research studies the fundamental position of environmental education in building sustainability-based practices while transforming people into environmentally aware citizens (Grimmette, 2014).

Components

Foundation of Environmental Education and Awareness:

Environmental education along with awareness training allows people to grasp complex human-environment relationships and generate knowledgeable actions that lead to sustainable growth. To achieve comprehensive environmental education both broad and detailed comprehension across various elements needs integration. The document investigates ten vital elements for constructing a sustainable ecologically literate community. A basic requirement for environmental awareness and system comprehension creates this initial aspect. It is crucial to interconnected systems. People must learn about how natural ecosystems operate through an understanding of biodiversity mechanics alongside water cycle dynamics and energy pathway functionality. The fundamental understanding created by this information empowers people to value maintaining natural systems equilibrium. Furthermore, an emphasis on Recognizing the interdependence of Human and natural systems enables Whenever individuals gain understanding they can evaluate environmental systems from a wider perspective (Gayford, 2019)

Developing Environmental Sensitivity and Problem Solving Skills:

Environmental sensitivity emerges as the second fundamental aspect. Sharing emotional intelligence creates responsibility toward environmental resources and responsibility towards the environment. People need encouragement to value nature for its own sake beyond everything it provides for human use. The psychological connections between people and nature develop most strongly when individuals experience nature personally by walking in nature or participating in ecological tours. Understanding environmental problems starts and ends with identifying their underlying causes alongside determining

their effects. Students learn the underlying sources behind climate change and deforest↓ station and pollution and biodiversity decline through education that prepares them for environmental stewardship. Through biodiversity loss petrochemical companies develop skills to recognize patterns while connecting different elements (Neal & Palmer, 2003). Through this experience it fosters critical analyses of deeds carried out by humans which cause environmental problems while opening students up to different sustainable options. Environmental education needs to teach essential skills which people require to solve environmental problems. Given environmental issues' complexity individuals need problem-solving abilities alongside critical thinking skills and decision-making competencies. Through skill training programs people develop their capability to build effective solutions which include waste-management systems also integrate energy-efficiency measures. Waste management systems, energy-efficient technologies, and reforestation initiatives (Grimmette, 2014)

Sustainable Practices, Ethics and Community Involvement:

The development of sustainable practice represents a fundamental aspect of the framework. Sustainable practices require intentional household and commercial strategies that reduce pollution while practicing resource conservation by using environmentally friendly products. People should adopt sustainable lifestyle choices because their benefits are specifically presented in ways that show their feasibility for regular use in everyday routines. The idea of environmental ethics establishes a foundational link for how people act and view things. By exploring ethical actions. A study of environmental stewardship principles teaches people about their obligations for protecting future populations. When we talk about non-human species rights as well as generational equity it helps encourage moral perspectives to influence environmental decisions (Kumar, 2023). Understanding environmental conservation requires fundamental knowledge about policy systems as well as principles of governance. Knowledge about environmental laws and international agreements together with awareness of policy-making procedures serves as the basis for individual involvement in governance systems. When people join governance through advocacy together with community engagement they create a stronger united power to defend the environment. Successful environmental education depends on community involvement together with their active participation. Community members contribute directly to environmental development through joint initiatives that include cleaning efforts and tree planting initiatives along with local conservation activities. When people actively engage in environmental

initiatives there emerges community-wide ownership combined with accountability toward environmental responsibility.

Innovation, Global Collaboration and the Future of Environmental Education :

Powerful tools from both media delivery systems exist for sharing information throughout society. Various forms of media serve as effective instruments to promote environmental knowledge. Organizations which use traditional platforms together with digital media spread environmental awareness across different audiences. Different environmental messages reach wide audiences successfully when targeted campaigns deliver scientific content through personal stories backed by both visual charts and dynamic video content (Kaul et al., 2020)

Ending our discussion we must emphasize the importance of developing resilience along with adaptability to confront environmental difficulties. People need to prepare themselves for adapting to sudden changing circumstances because climate-related emergencies become more frequent. Education on disaster preparedness. Education about disaster readiness combined with carbon-resilience tactics and resource conservation enables communities to respond to unpredictable events while building long-lasting development. Adding these key elements to environmental education programs helps deliver a complete approach to resolve environmental problems. Educational programs deliver knowledge along with skills and mental attitudes that allow people to make sustainable choices for natural resource protection which benefits generations into the future. In essence, environmental education and Both environmental education and awareness represent essential foundations of sustainability which require proactive societal collaboration at every level (Guerra- Mota etal.,2024). The implementation of ten essential fundamentals through curriculum standards and community initiatives and legislative frameworks provides a solid framework to reach worldwide sustainability objectives. Environmental education shows its greatest potential because it combines expertise in connecting humans with nature and driving people toward constructive actions and fostering responsible behaviors. Active human engagement combined with continuous learning will produce a sustainable future. Through environmental engagement humans create pathways for better relations between nature and human society. Environmental instruction needs to grow beyond classroom boundaries to create lifelong responsibility in daily practices. These educational initiatives find greater success by bringing

together educational institutions with non-governmental organizations and government bodies and private enterprises.

Multifaceted Nature of Environmental Education:

Environmental education stands essential for empowerment of marginalized communities. Risk falls heavily on women alongside indigenous peoples and residents with low-income. Environmental degradation. Education programs designed for each group's particular circumstances and obstacles will turn them into environment conservation participants. The solution of trans boundary environmental issues depends on worldwide knowledge sharing combined with environmental problem-solving efforts. Through international forums combined with research partnerships and knowledge-sharing platforms countries can study both their competitors' accomplishments and their challenges. Multiple organizations teaming up creates an ethos of world-wide solidarity alongside shared environment stewardship responsibilities. Environmental learning extends beyond transferring facts because it aims to completely transform personal approach and behavioral decisions (Arjen & Van Koppen,2015). A complete transition toward sustainability culture needs sustained dedication. Ambitious assessments and program enhancements secure the continued viability and appropriateness of training approaches that confront modern environmental problems. The sustainable future depends wholly on environmental education and awareness development. This document outlines ten essential components starting from u standing ecosystems which lead to resilience-indexed programs. Multifaceted nature of environmental education. People and communities can work toward creating harmonious relationships with nature through the combination of obtaining environmental knowledge with skill development and value implementation and taking concrete environmental actions. Collective action combined with innovation and strong dedication to planetary conservation will be essential for the attainment of these efforts (Bodin, 2017).

Challenges and Opportunities

Challenges in Implementing Environmental Education:

Development and the fight against the environmental challenges of the 21st century. As humanity faces Issues such as climate change, Deforestation, and biodiversity loss, educating people about the Importance of environmental Conservation becomes more critical than ever. However, despite its growing Significance, environmental education is Fraught with challenges that impede its Implementation and effectiveness. At This program realizes its distinct

purpose while addressing modern environmental problems. Opportunities to power individuals along with communities have distinct opportunities to participate in environmental protection efforts. Effective environmental education faces its biggest challenge from insufficient resources matched with weak infrastructure. The lack of financial support and educational resources keeps educational institutions across developing countries from delivering their intended environmental teaching goals. Scarcities of educational laboratories as well as equipment together with limited access to field exploration activities and practical tools impede the effective instruction of environmental science to students. Digital platforms also suffer from resource limitations because disparities in internet access together with unequal technology usage result in hindered understanding of environmental issues (Gough, 2016).

Barriers in Educational Approaches and Cultural Influences:

The field faces a significant challenge from an ongoing lack of properly trained specialists in environmental education. Most teachers lack certification in environmental studies and lack capabilities. Restricted access to modern learning tools together with limited technology adoption prevents students from accessing them. Students cannot develop deep environmental learning when they lack essential resources because theoretical information does not lead to true ability to teach complex cross-disciplinary subjects in their classes. Environmental education as an artistic endeavor presents Flawed approaches which stay on the surface. The current educational approach delivers basic knowledge without teaching essential analytical abilities for handling real environmental matters which affect students after graduation. The educational system presents educators with tight scheduling limits which force them to prioritize subjects like mathematics science and language arts. Harsh restrictions on teacher capabilities together with education system rigidity work against reaching total potential in environmental teaching methods in schools. Cultural barriers along with social factors block environmental lessons from showing their maximum effectiveness. In many communities, environmental concerns communities, environmental concerns Practical economic concerns overshadow natural resource sustainability or social challenges (Chibisova & Zvonova, 2020).

Integrating environmental education with current education learning materials proves to be a major barrier towards transformation. Educational institutions worldwide concentrate their efforts on standardized assessment systems because academic core knowledge remains their primary emphasis but neglect the potential of connected learning methods. Environmental education

tends to get separated into additional teaching subjects or extracurricular activities thereby minimizing its valued status for students and educators alike. Environmental issues become understated in classrooms which impedes student comprehension of the matter. Student understanding of environmental systems' interconnectedness with social systems and the economy becomes difficult because of this approach. Environmental education faces both difficulties and promising developments because of advanced speed in technological progress. (Orr, 1994)The innovative tools of technology include virtual reality simulations with interactive online courses and mobile applications which combine to provide engaging content that students can access anywhere. Also a continuing barrier is the digital divide which presents significant challenges mostly in poor rural areas Educational equity remains threatened because rural students and educators do not have access to digital tools or internet connectivity especially in underserved regions. Modern educational resources fail to reach students because of this structural inequality that worsens preexisting educational divides in learning environments. People need to consume modern educational materials though these tools may sometimes fail to deliver equivalent learning value when compared to practical experiences that connect students to nature.

Opportunities in Environmental Education:

Environmental education offers multiple prospects to develop positive developmental outcomes despite its current difficulties. Life learning potential represents a key strength which comes from environmental education applications. Potential to promote lifelong learning. Through environmental education individuals acquire the skills and requisite knowledge and mindsets to make enlightened environmental decisions that guide their reactions throughout their entire life. The curriculum builds problem-solving competencies and teaches systems thinking and critical thinking which readies students to deal with difficult environmental challenges in both stable and dynamic settings. The growing worldwide recognition of environmental problems creates an opportune setting for environmental education expansion. Governments, national Organizations and non-governmental organizations and government-supported entities with development goals have acknowledged that sustainable education needs must be included in their educational offerings. Through initiatives like the United Nations' Sustainable Development Goals (SDGs) countries now have a robust structure which enables environmental education integration into existing learning systems. Under SDG 4.7 educational approaches need to teach sustainable development combined with human rights protection alongside gender equality and environmental sustainability studies (Hungerford & Volk,

1990). The worldwide momentum behind environmental education establishes multiple partnership possibilities combined with financial backing and support for curriculum development projects. Recycling and saving energy are activities that can be described as sustainable. Furthermore, the growth of open educational resources for various environmental topics makes it easier for everyone to access this information no matter where they are located. (Tilbury, 2011)

The Role of Community Engagement and Innovation:

Another possible approach is the community based one. Having the local communities participate in the educational programs will allow students to really experience working with the environmental problems (Duda, 2022). Activities like community clean-up drives, tree-planting campaigns, and water saving projects are not only good for the environment, but they also serve as practical education for the students. Cultivating an attitude of personal responsibility towards the project and its components. This is of great importance in rural and other remote areas where development is dependent on social participation. At the same time, the inclusion of community leaders and other relevant individuals in the environmental education programs can help overcome cultural and social divides and enhance understanding and applicability of the programs to the context. Such integration is also feasible through a multidisciplinary and interdisciplinary approach to environmental education where thematic units are constructed on environmental education. Taking this example, science lessons can incorporate environmental issues (Hazarkhani & Parak, 2023). Educators can instill knowledge in children that pertains to ecosystems and climate change, as well as social studies so that children can learn about the consequences of civilization on Earth's resources. Children's art as well as children's books can be used to promote feelings about the environment while in Economics, children can learn about the costs related to the environment and its conservation. Showing students the interlinks between environmental challenges with other challenge does enables them to appreciate the importance of environmental education in their self and career aspirations. Collaborative partnerships are important in promoting environmental education. And those should also be able to partner with environmental NGOs, public authorities, and businesses to prepare and manage projects that respond to particular environmental needs. Students can engage in research work through collaboration with scientists while companies are willing to share useful knowledge regarding environmentally friendly practices and technologies.

Environmental education can empower people and communities to dress the pressing environmental challenges of our time by promoting lifelong learning, leveraging technology, adopting community-based approaches, fostering interdisciplinary learning, building partnerships, inspiring stewardship, and driving innovation. The success of environmental education can only be expected from the general collective efforts from educators, policymakers, communities, and individuals. As we tackle the complexities of the 21st century, environmental education will remain central to efforts of building a world that is at once more just, resilient, and environmentally responsive (Gough,2016).

Conclusion

In conclusion, environmental education and awareness are the backbone of a sustainable future. They provide the knowledge and motivation needed to confront the pressing environmental challenges of our time. However, for these efforts to be successful, they must be supported by adequate resources, widespread participation, and long-term ensure that environmental education Reaches everyone, everywhere, regardless of their Location, socioeconomic status, or Cultural background. By fostering people have to pool their efforts to enhance a sense of responsibility, enabling people to act, and support cooperation at the world level, we can make sustainability a reality rather than an ideal. United and persistent effort will prepare later generations to protect the earth and its ecosystems for all living beings' benefit. Environmental education and awareness are key tools for the mitigation of the impacts of global environmental challenges. The increasing rate of climatic change, pollution, loss of biodiversity, and depletion of resources all present threats to the planet, so education is pivotal in dealing with such issues. Environmental education empowers individuals to make informed decisions and contribute to the sustainability of the environment through the dissemination of knowledge, the development of critical thinking skills, and the cultivation of a sense of responsibility. Awareness and education are cornerstones of any meaningful environmental action, as They arm people with the knowledge needed to adopt behaviors that promote ecological balance. The relevance of environmental education lies in its capability of going beyond traditional knowledge transfer. While education has always been an instrument to cultivate intellectual development, environmental education differs because it is directed at real issues concerning the earth directly affecting each human being on the earth. Such education helps the student understand complex relationships between human societies and environment, how day-to-day decisions can lead to deep impacts on natural ecosystems. People come to realize the importance of conservation and guardianship of the environment-not only for themselves but also in the

future for others. In recent decades, environmental education has emerged as a key policy issue for nations and international policy makers. Internationally, the United Nations has been at the forefront of calling attention to the importance of education in achieving sustainable development. Several countries have thus integrated environmental education into their school system, universities, and colleges Specialized courses, workshops, and activities to raise awareness on environmental issues are now being offered in community programs.

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CHAPTER- 02

TRANSFORMING INDIA: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT

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Abstract

Sustainable development has emerged as a central theme in global discourse, capturing the attention of the international community. Countries across the world, along with various stakeholders, are committed to implementing this plan through collaborative partnerships. There is a firm resolve to liberate humanity from the clutches of poverty and to heal and safeguard our planet. Over the years, the SDG India Index has shown consistent improvement, offering a detailed and comparative evaluation. The adoption of the 2030 Agenda and its Sustainable Development Goals (SDGs) is widely recognized as a milestone in global sustainability efforts. Numerous national political systems and civil society actors now actively hold public officials accountable for fulfilling their pledge to leave no one behind. The SDGs align closely with India's own national development goals, which played a pivotal role in the formulation of the United Nations Sustainable Development Agenda 2030. More recently, India's progress under the SDG framework—compiled by NITI Aayog for 2023–24, reflects continued advancement at the national level. This success stems from the effective implementation of social safety nets, infrastructure projects, and financial inclusion initiatives. In a post-pandemic world, where rebuilding stronger and better is the shared goal, SDG-oriented efforts and their tracking are more crucial than ever. Having already crossed the halfway mark towards realizing the SDGs, this paper will

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delve into India's vital contributions in shaping and striving to fulfill these goals within the committed timeframe.

Keywords: SDG's, Niti Aayog, Indian Economy, Transformation.

Introduction

Social sustainability is the ability of a social system to function at a defined level of social well-being and harmony indefinitely; in this context, a social system may be country, family or an established organization. Manifestations of a socially unsustainable system include issues like pandemic poverty, low educational rates, widespread injustice and conflicts and war. The term 'Sustainable development' (SD) necessitates a precise understanding of sustainability, development, society, economy and environment are major players in ensuring SD (Pizzi et al., 2021). Development ensures an improvement in both the quality and quantity of life. It is the accumulation of human capital and its effective application to the advancement of an economy. It advocates for the harmonious integration of ecological integrity, responsible governance, social cohesion and a viable economy. There are various definitions of SD. The most generally used and illustrative definition of SD is one that emphasizes balance in the social, economic and environmental protection, social reform and people's empowerment (Sachs, 2012). SD serves the demands of the present generation while preserving the ability of future generations to meet their own needs. The key idea of SD is ensuring that development in a life sustaining process (Stafford-Smith et al., 2017). Fifty per cent of all jobs globally. As both agents and beneficiaries of inclusive development, MSME's are critical actors in accelerating the implementation of the SDGs. Their development is critical for fostering job creation, economic progress and ensuring that no one falls behind. With 17 goals, 169 specific aims and 232 targets, the SDGs aim to promote and tackle other global issues like climate change, economic inequality, innovation, sustainable consumption, peace and equity. They are among the best tools to address the challenge of creating 600 million new jobs by 2030, especially for the government to put in place enabling policies for and by youth (Hák et al., 2016). Furthermore, India's emphasizes on inclusive prosperity and strategic prominence in global affairs makes its presidency critical. India also functions as a worldwide sounding board, ensuring that its issues are

heard on the global scale. Finally, India's participation in health care, particularly during the Covid-19 pandemic, puts it as a supporter of universal, high quality and affordable health services. The country has implemented several initiatives and strategies to boost the growth rate (Khalid et al., 2021). India, a country with 1.4 billion population, fierce competition to provide the basic demands of a healthy lifestyle. Keeping this in mind, SD is critical for meeting the demands of the present generation without compromising the needs of future generations (Panda & Mohanty, 2019).

NITI Aayog, a think tank established by the Indian Government in January 2015, has been tasked with overseeing implementation of 2030 Agenda. To ensure inclusive participation and faster implementations of SDG's, NITI Aayog has conducted a mapping of various Central Government Ministries against each agenda 2030 goal and target and ministers have come forward with their full support for raising public awareness about 2030 agenda. This monitoring exercise is being carried out in parallel by NITI Aayog to ensure policy debate and outcome budget discussions for the implementation of the 2030 Agenda, as well as the internalization of the Agenda as the guiding principle right from the start (Panda & Mohanty, 2019). Moreover, the institution is tasked with approving and monitoring Ministers' outcome budgets in order to drive program implementation in accordance with Agenda 2030. In addition, regular consultations with stakeholders are conducted to ensure coherence in SDG implementation across different sectors and states. A dedicated Central Ministry for Local Self Government, working alongside corresponding state-level ministries and grassroots local self-governments, is actively ensuring inclusive participation from all stakeholders. Many of the Government of India's flagship initiatives, such as the Pradhan Mantri Jan Dhan Yojana aimed at financial inclusion, Make in India, Smart Cities Mission, Start-Up India, and Digital India—align seamlessly with the SDG 2030 vision. Likewise, social initiatives like 'Beti Bachao, Beti Padhao' promoting gender equality, along with major infrastructure and welfare programs like 'Housing for All', 'Power for All', and the 'Clean India Mission', reflect strong alignment with global goals (Stafford-Smith et al., 2017). Significant momentum has also been generated through efforts to boost road connectivity, particularly to rural areas exceeding a threshold population. Altogether, these integrated efforts are a testament to

India's dedication to advancing the Sustainable Development Goals in a holistic and inclusive manner. This chapter gives the detail about the significance of the sustainable development, how to assess these goals through economic measures. The paper explores key issues that are both pressing and highly important in today's rapidly evolving and interconnected world. It also analyze the country and strength, weakness, opportunities and challenges in the context of India in the G-20 Summit.

Sustainable Development and its Significance

Sustainable Development (SD) is a method of addressing people's present demands while allowing future generations to meet their own. Many of our natural resources are finite, thus it is our civic responsibility to use them responsibly. That's why people are increasingly turning to more sustainable products and technologies. SD aims to use resources in a way that doesn't disrupt the natural balance (Stafford-Smith et al., 2017).

In simple terms, SD is similar to caring for large, shared gardens. We all want to choose fruits and vegetables for our needs today, but we also want to ensure that there is enough left for people to enjoy tomorrow and the following days. As a result, we must use the garden's resources properly and avoid causing damage to ensure that it can continue to provide for everyone in the future (Panda & Mohanty, 2019; Pizzi et al., 2021).

Sustainable Development Goals for 2030

The Sustainable Development Goals (SDGs), also referred to as the Global Goals, represent a universal commitment to end poverty, safeguard the environment, and ensure that every individual in all United Nations member countries enjoys peace and prosperity by the year 2030. These goals are structured around six central themes: dignity, people, the environment, partnerships, justice, and prosperity. Extending beyond mere economic progress, the SDGs emphasize the importance of social development. They are designed to tackle a wide array of pressing global issues including climate change, economic inequality, innovation, sustainable consumption, peace, and equity. Altogether, the SDGs comprise 17 overarching goals, supported by 169 specific targets and monitored through 232 indicators.

India and Sustainable Development

India, as one of world's fastest growing economies, presents a distinct set of problems and opportunities in its quest of SD. India is a country known for its tremendous diversity, with religions, communities and individual having diverse levels of access to key services, opportunities and resources. Despite substantial economic progress in recent decades, major discrepancies remain in sectors such as public health, education, gender equality, financial inclusion and economic empowerment. These gaps continue to impede India's progress toward SD and equity for its people (Jha & Rangarajan, 2020; Sarkar & Bharat, 2021).

However, in recent years, the notion of 'Sustainable Development' has been based on three interconnected and mutually reinforcing pillars: Economic development, social development and environmental protection. It encourages human civilization to achieve their own needs without compromising future generations' potential to do the same. At the 2015 UN SD Summit, the UN member states accepted the 2030 agenda for SD and its 17 SGDs (Sachs, 2012). The 2013 agenda continue to be the world's most comprehensive blueprint for SD. While the SDGs were originally intended to help the world's poorest countries, they now serve as a tool for all countries to improve their importance on topics of common interest. Long before joining the UN, India implemented numerous policies and plans to achieve its sustainable development goals. According to the SGD Index Rank report, India ranks 109th out of 166 countries. The SGDs index score is 63.99%, which represents the percentage of overall SGD goals attained by the country as of now (Sarkar & Bharat, 2021). The countries overall SGDs score rose from 66 in 2020-21 to 71 in 2023-24. PM Modi has altered India's foreign policy by emphasizing the global common good. India's leadership in the G20 aims to identify long term and appropriate solutions to global concerns such as climate change, new technologies, food and energy security (Ali et al., 2021). NITI Aayog is the nodal institution for accomplishing SGDs, driving the 2030 agenda with a spirit of cooperative and competitive federalism. The Prime Minister' emphasis on 'Sabka Sath, Sabka Vikas' reinforces the notion of 'Leaving No One Behind'. India's support for 'Vasudhaiva Kutumbakam' (The World is one Family) and its role in

elevating and the voice of the global south reflect the country's commitment to SD.

Make in India

The Make in India program is a commendable initiative by the government that aims to promote India as a major manufacturing powerhouse. In a short period of time, the plan identified major doable for attracting investments in diverse industries, promoting innovations, training skills and improving state of the art manufacturing infrastructure. This program has the ability to create millions of jobs opportunities, deploy a large young population and position India prominently on the global industrial map (Wani et al., 2016). Since, Make in India project would provide millions of job opportunities for the young population, it will be critical to give skill education to upgrade their abilities and prepare them for rising demand for trained workers. As a result, Skill India program will be important for Make in India program which will further percolate to the rural sectors of the economy (Wani et al., 2016).

Transforming through skill development

PM Modi announced the Skill India campaign on 15th July, 2015. Under this campaign, the government has taken many measures such as NSDM, PMKVY and skill loan scheme. The program aims to train young people so that they can find work and enhance their entrepreneurial skills. The fundamental aim of Skill India is to boost confidence, improve productivity and provide direction through effective skill development. Skill India will offer blue-collar jobs to the youth. Skill and expertise are critical in overcoming such obstacles and assisting India on its path to endless growth. For this, skill development is a requirement, as it not only helps the country's youth gain vital skills but also helps in economic development of a country.

Transforming through Digital India

Digital India is a comprehensive umbrella initiative that integrates efforts from various government ministries and departments under a unified vision. It consolidates a broad spectrum of ideas and strategies,

allowing them to be implemented cohesively toward a larger national objective. While each component operates independently, it also contributes to the overarching mission of a digitally empowered nation. The initiative is adopted across the entire government, with the Department of Electronics and Information Technology (DeitY) taking charge of its coordination (Scholz & Brandi, 2017). Digital India is built on nine foundational pillars: Broadband Highways, Universal Access to Mobile Connectivity, Public Internet Access Program, e-Governance: Reforming Government through Technology, e-Kranti: Electronic Delivery of Services, Information for All, Electronics Manufacturing, IT for Jobs, and Early Harvest Programs. Each of these pillars represents a complex program involving multiple ministries and departments, reflecting the integrated nature of the Digital India movement (McBride et al., 2019)

We are one Earth, one family and we share one future

This is the group of 26's (G20) first sentence. The G20 leaders convened during 9-10 September 2023 in New Delhi, India. Implementing the 2030 Agenda will necessitate new investment across a wide range of industries, Drawing on the G20 multiyear development agenda and the G20 agenda for robust, sustainable and balanced growth (Jha & Rangarajan, 2020).

During the last G20 conference in New Delhi, conducted under the Indian presidency, the leaders from several countries expressed concerns about the implementation of the agenda 2030, seating unsatisfactory as the global progress on Sustainable Development Goals (SDGs). The members highlighted the pressing need for concerted efforts to fully and effectively implement the 2030 Agenda for a greener planet and to reduce socio-economic gaps among the developed and developing countries. The initiatives of G20 nations provide a ray of hope for a more sustainable and carbon- neutral future. The primary goal of SD is to strike a balance between population, various resources, environmental and development concerns (Scholz & Brandi, 2017). The G20 is a perfect blend of geographies linked by common goals, aimed at addressing global economic and financial concerns. The G20 has grown beyond macroeconomics measures to encompass key global issues such as climate change, terrorism and poverty. The G20 has continually prioritized food security, productivity

and sustainability, with current focus on sustainable resource use. They also priorities collaboration in agro-food value chains and assist rural development activities. During this cycle and the Indian presidency, it endorsed high level lifestyle for SD concepts. The G20 has indicated its support for the latter, more environmentally responsible route.

India's G20 Presidency and the dawn of a New Multilateralism

A 2019 report by the Organisation for Economic Cooperation and Development (OECD) and the United Nations Development Programme (UNDP) highlights the G20's vital role in achieving the Sustainable Development Goals (SDGs), given that the group accounts for 85% of the global GDP, 75% of global trade, and nearly two-thirds of the world's population. One of the key priorities on the G20 agenda is SD, which integrates environmental, social, and economic dimensions across both the Global North and South (McBride et al., 2019). This agenda aligns with the 17 SDGs that are to be realized by 2030, aiming to secure the well-being of both people and the planet. The foundation of this vision stems from the Brundtland Commission's report *Our Common Future*, which defines SD as the ability to meet present needs without compromising the capacity of future generations to meet their own (Brundtland, 1987).

The G20 or Group of twenty is an international government forum consisting of 19 countries and the European Union that handles global financial challenges. The inaugural G20 Summit to take place in 2008 in Washington DC, in the United States of America. India has actively used its membership to advance its economic interest, particularly by gaining market access for its goods and services. As it assumes, the G20 Presidency in 2023, India is positioned to play a key role in shaping the global economic agenda. Climate change, the Covid-19 pandemic and conflicts such as those in Ukraine are among the topics covered on the agenda. The New Delhi Declaration, a momentous and path breaking document, was adopted with complete accord on every development and geo-political issues.

India's G20 Presidency's top priorities

- **Climate Finance and Green Development**: One of the pillars of India's presidency is its focus on addressing climate change. It aims to ensure equitable energy transitions, especially for

developing countries, while advancing climate technologies and financing.

- **SDGs Acceleration**: India is still dedicated to accomplishing the SDGs set forth in the 2030 Agenda. India wants to encourage international collaboration in this effort, with emphasize on reducing the COVID-19 pandemic's effects.
- **Technological Transformation**: In domains such as financial inclusion, digital public infrastructure, and technology-driven growth in sectors like agriculture and education, India champions a human-centric approach to technology and the sharing of information.
- **Reforming Multilateral Institutions:** India remains dedicated to reshaping multilateralism into a more inclusive, accountable, and representative global framework that is equipped to tackle the challenges of the 21st century.
- **Women-led Development**: Understanding the value of women's empowerment and representation, India seeks to advance inclusive growth and development by focusing on women's employment and closing the gender gap.

The Dynamics of 2030 ka Bharat

The dynamic aspect of 2030 Ka Bharat (SDG Goals) is what makes it so exciting. The India of 2030 is a journey that is already well on. Here are some of the important forces fueling this transformation.

Technology: The Digital Revolution

India is a global innovation hub, with a thriving startup ecosystem and a focus on technology as a tool for progress (SDG Goals) 2030 Ka Bharat.

- **AI Everywhere:** Artificial Intelligence is now integrated into everyday life, from smart cities to personalized healthcare.
- **The emergence of Startups:** India has a flourishing startup scene that rivals Silicon Valley. Nearly every month, a unicorn is born!

- **Digital Literacy:** Digital literacy is a fundamental skill. Because internet connection is so reasonably priced, even the most towns are connected by 2030.

Socio-Cultural Diversity: Unity in Plurality

One of the most wonderful features of 2030 Ka Bharat (SDG 2030) is how it celebrates it diversity. The country's cultural tapestry is preserved while evolving with the times:

- **Cultural Renaissance**: Ancient art forms such as classical music to traditional crafts are flourishing while fusion art is on the increase.
- **Languages Unite:** With greater linguistic diversity, language preservation movements are more powerful than ever. Translation technologies make India genuinely bilingual.
- **Festivals Galore:** The celebrations in 2030 are larger than ever, with festivals of all faiths celebrated with fervor and unity.

Economy: A Global Powerhouse

The economy is a major force in the world. India has established itself as a major economic force in the world by 2030.

- **Manufacturing Power**: With numerous domestic brands taking over foreign markets, "Made in India" has replaced "Make in India,"
- **Dominance of the Service Sector:** The services sector, which includes IT industries and the hospitality, has grown rapidly and created millions of employments.
- **Sustainable Methods:** Sustainability is a way of life, not just a trendy term. India is at the forefront of the global use of renewable energy.

Environmental Consciousness: A Greener Tomorrow

2030 Ka Bharat (SDG 2030) emphasizes the need to preserve the environment for future generations.

- **Clean Energy Revolution**: Solar and wind power dominate the energy landscape, reducing India's CO2 footprint.
- **Green Initiatives:** Reforestation programs and eco-friendly practices are common, revitalizing India's rich forests.
- **Waste Management Innovation**: Innovative waste management technologies have helped India become cleaner than ever before.

Obstacles on the road to 2030

1. **Geopolitical Tensions and Conflicts:** Trade wars, military conflicts and economic sanctions are the results of growing rivalry between the world's superpowers, including the US, China and Russia. Instability, supply chain disruptions and humanitarian crises are all consequences of regional conflicts like conflicts between Russia and Ukraine in the Middle East. Digital warfare and cyber security threats are also growing, raising the stakes for critical infrastructure and national security.

2. **Economic Uncertainty and Inflation**: The world economy is dealing with rising interest rates, inflation and debt difficulties in a number of nations. As emerging countries struggle to recover from financial downturns, economic disparities are growing. Economic development and innovation may be slowed by the trend toward de-globalization, where countries prioritize home production above international trade.

3. **Environmental degradation and Climate Change:** Agriculture, water security and coastal towns are all under risks due to increasing frequency of extreme weather events, rising global temperatures and environmental damage. Due to lack of technological development in sustainable energy, political opposition or economic limitations, many nations are finding it difficult to enact effective climate policy.

4. **Ethical Issues and Technological Disruptions:** Industries are changing because to the quick growth of biotechnology, automation and artificial intelligence, but there are also issues with privacy, ethical use and employment displacement. Governments are finding it difficult to AI and other cutting – edge technology while making sure they advance human kind without endangering it. In the digital age,

misinformation and cybercrime are increasingly becoming a more serious problem.

5. Challenges in Public health and upcoming pandemics: Despite the lessons learnt during COVID- 19 aging populations, antibiotics resistance and the possibility of future pandemic continues to put strain on healthcare systems. The disparity in access to healthcare between wealthy and developing countries remains a significant obstacle.

Conclusion

As we approach the culmination of the 2030 transformation journey, one truth becomes increasingly clear—India's evolution is not just a vision, but a dynamic fusion of tradition and innovation that is steadily unfolding. The G20 has played—and will continue to play—a pivotal and unique role in driving forward the 2030 Agenda for Sustainable Development. India is steadily progressing on its path to becoming one of the world's top two economies by 2047. To achieve this ambitious goal, strategic vision documents are already being drafted with inputs from a diverse array of stakeholders across all sectors. The choices and actions we take today will shape the outcomes of tomorrow. As one of the world's oldest civilizations, India has always embraced global cooperation and continues to extend an open invitation to partners in building a prosperous future for all. In implementing the 2030 Agenda, India remains committed to delivering benefits for both current and future generations. We reaffirm our dedication to upholding international law and ensuring that this global agenda is carried out in a way that aligns with the legal rights and responsibilities of nations. Undoubtedly, the Indian government remains resolute in its pursuit of the Sustainable Development Goals (SDGs).

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CHAPTER-03

GREEN MARKETING: CHALLENGES AND OPPORTUNITIES FOR INDIA

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Abstract

The increase in global awareness of ecological issues and the increasing demand for sustainable products has led to the expansion of green marketing in India. Going green concept which emerged in 1980s is evolving continuously over the time and is gaining importance due to issues like pollution and conservation of natural resources. Indian organizations are increasingly implementing the green marketing strategies to attract consumers and maintain competitiveness in the environment conscious market. In this modern era of globalization, it has become a challenge to retain consumers and also keep our biological environment protected. Through this chapter the challenges and opportunities for green marketing in the Indian perspective have been investigated. It emphases on factors such as consumer awareness, government regulations, Corporate Social Responsibility (CSR) and the role of companies in promoting eco-friendly practices. Additionally, it assesses the potential benefits and future trends in green marketing in India, along with the noteworthy impediments businesses face while implementing sustainable marketing strategies.

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Keywords: Environment, Green Marketing, Sustainability, Eco-friendly, Corporate Social Responsibility (CSR).

Introduction

Green marketing is the practice of indorsing products or services based on their environmental benefits. American Marketing Association defines, green marketing as the marketing of products that are assumed to be environmentally harmless. It refers to holistic marketing thought wherein the production, marketing, consumption and disposal of products and services is done in a way which is less harmful to the environment. In the varying business environment together marketers and consumers are mindful of the need to shift to green products. Green marketing stresses on manufacture of eco-friendly products which means that the produced goods have a negligible influence on the environment. The goods produced have sustainable production process wherein the products are formed through practices that diminish waste and energy consumption and the organizations being aware of their environmental accountability that emphases on reducing the environmental impact of the products throughout the product lifecycle.

Polonsky (2011) in the current scenario of growing environmental issues and the need for sustainable development, the universal business landscape has undergone a transformation in recent years. Due to which the concept of green marketing has risen, which encompasses the development, promotion and distribution of products and services that are ecologically safe.

In the Indian perspective, the progression of green marketing has been meticulously related to the country's economic liberalization in the early 1990s and its subsequent rapid industrialization. As India unwrapped its markets to international competition as a consequence it became all the time more exposed to international environmental benchmarks and sustainability practices. This exposure, along with increasing domestic environmental matters, has progressively moved the emphasis of Indian businesses towards new sustainable practices (Manaktola & Jauhari, 2007). In India, green marketing is gaining recognition as a response to amassed concerns about climate change, pollution, and the exhaustion of natural resources.

India is one of the world's rapidest growing economies and a noteworthy contributor to worldwide carbon emissions and is at a critical stage, confronting both challenges and opportunities in adopting green marketing strategies (Kumar & Ghodeswar, 2015).

Need for Green Marketing

Green marketing has arisen as a solution to the innumerable challenges being confronted wherein the business houses have got the opportunity to distinguish themselves in the market and cater to the mounting fragment of environmental aware consumers. (Jain & Kaur, 2004). The Indian government has taken steps to enhance sustainable development and environmental protection by means of countless initiatives and guidelines. The National Environment Policy of 2006 gives an outline for amalgamating environmental concerns into development planning (Ministry of Environment & Forests, 2006). Moreover, programs like the National Mission for a Green India focus to expand forest cover and enhance ecosystem services (Ministry of Environment Forest & Climate Change, 2014). In the increasing global pressure to address climate change, these government initiatives have created a favourable environment for green marketing in India. Numerous Indian companies, especially in sectors such as fast-moving consumer goods (FMCG), automobiles, and information technology, have started to incorporate sustainability in their business strategies and marketing efforts (Saxena & Khandelwal, 2010).

Key Strategies for Green Marketing

- **Innovation of the product:** One of the vital ways to involve in green marketing is through product innovation. This includes development of eco-friendly products or transforming existing ones to decrease their environmental influence. For example, companies may use recyclable materials, reduce packaging waste, or design products with energy effectiveness.
- **Transparent Communication:** Business organizations should clearly communicate the environmental uses of the products or services, being offered by them which will provide consumers with true and verifiable information. Eco-labeling, sustainability reports, or dedicated segments on company websites are the means through which it can be attained.

- **Buyer Education:** Countless consumers are ignorant of the environmental concerns of their buying decisions. Green marketing encompasses educating consumers about the significance of sustainability and enabling them to make informed choices. Companies can do this with the help of advertising campaigns, informative content, or joining hands with environmental bodies.
- **Optimization of Supply Chain:** Sustainability goes beyond the consumption final product to include whole supply chain network. Companies can apply green marketing strategies by procuring materials sensibly, decreasing carbon emissions during transport, and endorsing fair labor practices. By allying with dealers which commit to sustainability, businesses can improve their brand reputation and trustworthiness.
- **Corporate Social Responsibility (CSR):** Adopting Corporate Social Responsibility is another efficient way to validate a company's commitment to environmental sustainability. Whether it's backing up reforestation projects, investing in renewable energy, or taking part in community clean-up efforts, CSR activities can intensify brand loyalty and attract socially aware consumers.

Challenges for Green Marketing in India

Lack of Consumer Awareness

One of the major challenges being faced by green marketing in India is the low level of consumer consciousness concerning the environmental impacts of their buying decisions. Urban consumers have become more aware of sustainable consumption while the rural areas still lag in understanding the significance of green products.

High Costs involved in Green Products

Eco-friendly products tend to have higher manufacture costs due to sustainable sourcing, moral labor practices, and the use of progressive technologies for decreasing environmental effect. These costs are then

levied on the consumers which makes green products less affordable for a substantial percentage of the population, particularly in cost-sensitive markets. The business houses need to learn to manage activities in a way that they have adequate profits following sustainable practices.

Insufficient Government Regulations

Indian government has initiated many regulations and policies such as the National Action Plan on Climate Change (NAPCC), National Environment Policy of 2006, National Mission for a Green India etc. but still there is a scarcity of clear and complete regulations explicitly targeted at promoting green marketing. The nonexistence of a strong regulatory framework for green certifications and product labeling makes it difficult to build trust among consumers.

Green washing

Green washing, or the act of misleadingly depicting a product as environmentally friendly, is a significant issue. In the absence of standardized regulations and certifications, companies may make deceiving claims about their products' environmental credentials, which undermines the credibility of green marketing efforts.

Supply Chain Complexities

The implementation of sustainable practices within supply chains can be challenging due to the complicated and fragmented nature of Indian supply chains. Various producers in India are still reliant on non-sustainable resources, and transitioning to green supply chains needs substantial investment in latest technologies and practices.

Cultural Challenges

Despite increasing concern generally environmental consciousness amongst Indian consumers is comparatively low. Traditional consumption patterns and an inclination for acquainted products can make it challenging to present new eco-friendly options. India’s diverse

market with noteworthy dissimilarities in income levels, education and cultural practices makes it challenging to apply one size fits all green marketing strategy.

Building Credibility: Business houses need to build faith of customers in their products by being transparent and having honest commitment to sustainability which requires these business units to make some significant changes in their business activities.

Opportunities for Green Marketing in India

Emerging Environmental Consciousness

With the increase in worldwide environmental concerns, there is an increasing fragment of environmentally aware consumers in India, predominantly in urban areas. Consumers are becoming more attracted towards products that support sustainability, and companies that can adhere to fulfilling customers' needs will gain a competitive advantage.

Government Initiatives

The Indian government has taken numerous initiatives concerning the encouragement of sustainability, including the promotion of renewable energy, electric vehicles, and waste management initiatives. Companies that bring into line their marketing strategies with these national initiatives can definitely get benefits from government incentives and a good public image.

Corporate Social Responsibility (CSR)

Countless Indian businesses organizations are amalgamating sustainability into their corporate social responsibility (CSR) plans. This alignment with green marketing can boost brand reputation, build consumer loyalty, and lead to opportunities for partnerships with environmental organizations.

Innovation and Technological Advancements

Advancements in technology are making it simpler for businesses to manufacture and market green products. For insistence, innovations in packaging, product design, and waste management can diminish environmental influences and make eco-friendly alternatives more reasonable for consumers.

International Markets

Indian companies can influence the global inclination towards sustainability by marketing green products to international markets. There is an increasing demand for sustainable products in developed economies, and Indian companies that are able to meet these benchmarks have the opportunity to increase their customer base.

Promoting Green Consumerism

Educational campaigns, partnerships with NGOs, and marketing activities aiming on environmental influence can help to move consumer behavior toward green consumption. Companies which invest in educating their consumers on the environmental paybacks of their products can escalate demand for green products.

Examples of few Indian companies that are leading the way in green marketing:

Tata Group: The Tata Group has made noteworthy developments in amalgamating sustainability into its business model, particularly in its energy and automobile sectors. Tata Power and Tata Motors, for example, have merged green technologies like solar energy and electric vehicles.

ITC: ITC emphases on green marketing by encouraging its products made out of sustainable resources like its paperboards and packaging, and its initiatives to reduce carbon secretions. It’s "Well-being Out of Waste" (WOW) campaign emphases on promoting awareness, separation, collecting, and recycling municipal solid waste through the complete value chain.

Ultra Tech cement: Ultra Tech, one of the biggest cement manufacturers in India, is constantly committed to playing a noteworthy role in developing effective and responsible solutions to preserve the environment. The company has faced a drop in greenhouse gas emissions, showcasing their obligation towards decreasing their carbon footprint.

Amul: As a dairy company, Amul has introduced sustainable farming practices and eco-friendly packaging to align with consumer demands for greener substitutes.

TCS: To address climate variations and its effect, TCS is carrying out various eco-friendly initiatives throughout the region like tree plantation drives in various countries, as well as clean up activities for water bodies and public spaces. Through its varied efforts covering different countries and cultures in the Asia Pacific zone, TCS exhibits sincere commitment to its responsibility towards the environment.

Dabur: Dabur, a well-recognised healthcare organization in India, has launched its mission to work together with the government in achieving their goal of an open defecation-free (ODF) nation through effluent treatment system (ETP). To contribute to this initiative, Dabur HD plans to construct 1,200 rural household toilets across 28 villages.

Hindustan Unilever: Hindustan Unilever Limited (HUL) is India's most renowned FMCG Company, having a rich legacy of more than around eight decades. In their commitment to environmental sustainability, HUL project focused on barren land recovery and water conservation and harvesting.

Reliance Industries Limited: RIL focuses in refining, manufacturing refined petroleum products, and petrochemicals like basic chemicals, fertilizers, nitrogen compounds, plastic, and synthetic rubber in their primary forms.

Larsen and Toubro: Larsen and Toubro (L&T) Company, an organization that prioritizes environmental preservation, has carried out many initiatives to safeguard the ecosystem. This involves setting up of water-positive campuses and carbon-neutral sites.

ONGC: The ONGC group is dedicated to encouraging usage of clean fuel in both its operations and transportation aspects. The setting up of electric vehicles aimed not only at reducing dependence on fossil fuels

but also at bringing down air pollution levels. ONGC has also implemented an inclusive strategy for controlling water resources at its different locations.

ITC: ITC's notable "Well-being Out of Waste" (WOW) drive focusses on nurturing consciousness, separation, gathering, and reusing of municipal solid waste throughout the entire value chain. Around 89 lakh Indians get benefit from this ground-breaking initiative.

Ultra Tech cement: in the recent years the company experienced a decrease of over 1.1% in greenhouse gas discharges, showing their commitment towards reducing their carbon footprint. As part of their sustainable efforts, the use of recycled materials also increased They have also invested in waste heat recovery systems to further enhance their eco-friendly initiatives.

Infosys: Infosys exhibits its commitment to environmental and sustainable practices across its campuses with the help of energy conservation initiatives like water saving measures throughout their campus solar PV plants and optimized electricity usage. Infosys stands as an exemplary model of corporate responsibility and environmental consciousness.

Myntra: India’s biggest fashion retailer Myntra has almost eliminated single-use plastic from its packaging. They have swapped bubble wraps, plastic tapes, and plastic covers with shredded materials, paper tapes, and paper boxes and covers.

Recommendations for Companies to overcome challenges:

- Educate consumers: Companies should conduct awareness programs through which consumers can be educated on the environmental benefits of green products also rural consumers can be tapped.
- Affordability: Green products should be made inexpensive through innovations in production, packaging, and distribution.
- Standardization: Companies need to stick to international benchmarks for environmental certifications to build consumer confidence.

- Sustainability in Supply Chain: Businesse houses need to invest in building greener and more proficient supply chains, which may lead to cost decreases in the long run.
- Collaboration with Government and NGOs: Tie ups with the government and environmental organizations can increase trustworthiness and help companies meet sustainability targets.

The Role of Government and Policy Makers

The Indian government plays a vital role in modelling the environment for green marketing. Policy involvement can significantly impact both consumer behavior and corporate practices. Some key areas where government action can aid green marketing include:

- Establishing and clarifying environmental guidelines: Making clear, consistent, and implementable environmental benchmarks can provide businesses with guidelines to work and increase consumer confidence in green claims.
- Providing incentives: Offering tax benefits, subsidies, or other financial incentives for eco-friendly products and practices can help decrease the higher costs associated with green initiatives (Kumar, 2016).
- Supporting research and development: Government financial aid for research targeting towards sustainable technologies and practices can increase innovation and make green practices more accessible to businesses (Nair & Menon, 2008).
- Promoting eco-labeling: Developing and encouraging standardized eco-labeling schemes can help consumers make well-versed choices and diminish confusion in the marketplace (Maheshwari & Malhotra, 2011).

Public procurement policies: Integrating environmental criteria into government procurement policies can form a significant market for green products and services (OECD, 2015).

Future Prospects:

As India continues to deal with the dual problems of economic development and environmental protection, the role of green marketing

becomes very important. The recent trends in business environment predict a favourable future for green marketing in India:

- Growing environmental awareness: As the education levels are increasing and information has become more reachable, environmental consciousness among Indian consumers is increasing, potentially increasing demand for green products (Kumar & Ghodeswar, 2015).
- Technological advancements: Innovations in clean technologies are likely to make green products more reasonably priced and accessible over time (Nair & Menon, 2008).
- International pressure: As India becomes more unified into the global economy, international pressure to implement sustainable practices has intensified, potentially encouraging more companies towards green marketing.
- Urbanization: The increase of urbanization in India is expected to increase environmental concerns in cities, potentially making new markets for green products and services (Sankhe et al., 2010).
- Study of Consumer behaviour: More elaborative researches should be done on the factors influencing green purchase decisions in different segments of the Indian market to inform marketers of the consumer expectations.
- Policy effectiveness: finding out the impact of different policies regarding green marketing adoption can help in making effective government strategies.
- Sector-specific strategies: Exploring green marketing approaches made according to different industries can provide valuable insights for businesses across various sectors.

Conclusion

Green marketing presents both significant challenges and opportunities for businesses in India. While challenges like elevated costs, consumer awareness gaps, and regulatory difficulties exist, the rising environmental awareness of Indian consumers, combined with government support for sustainability, creates ample opportunities for businesses to succeed in green marketing. As the market for sustainable

products continues to advance, companies that can efficiently navigate these challenges will be positioned for long-term growth in the green economy.

Marketers also have the responsibility to make the consumers understand the need for and benefits of green products as compared to non-green ones. Consumers, industrial buyers and suppliers need to understand the positive impact of the environment-friendly products. Green marketing assumes even more importance and relevance in developing countries like India. (Dutta Shubha, 2024)

India can overcome challenges and embrace green marketing to tap into the growing eco-conscious market. It is evident that with the right strategies, green marketing can be both an ethical and profitable approach in India's dynamic marketplace.

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CHAPTER-04

GREEN TECHNOLOGIES AND INNOVATIONS: PATHWAYS TO ECO-RESILIENCE

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Abstract

Green technology and innovation represent a transformative approach where environmentally friendly solutions are developed to prevent ecological degradation and conserve natural resources. Often referred to as clean or environmental technology, green technology aims to meet society's needs and desires without compromising the planet's well-being. By fostering a balance between development and sustainability, these innovations ensure that natural resources are utilized responsibly, avoiding depletion and promoting environmental harmony. At its heart, green technology emphasizes designing product with repetitive reusability in mind, creating systems that reduce waste and maximize efficiency. Another key goal is to repair the damage inflicted by climate change, offering tools and strategies to restore the planet's ecosystems. This paper explores the landscape of green technology and innovation in developing countries, with a particular focus on India as a case study. India provides a lens through which the challenges and opportunities of green innovation in other developing

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countries can be understood. The analysis highlights the pressing need for sustainable solutions, the hurdles faced in their adoption and the potential for these innovations to drive long-term growth. The insights and recommendations presented aim to guide policy makers and innovators in identifying barriers and formulating strategies that can drive green innovation forward. By aligning development with ecological preservation, green technology becomes not just a solution to climate change but also a catalyst for a more sustainable and equitable future.

Keywords: Environment, Green Technology, Innovation, Sustainable.

Introduction

The demand for sustainable solutions is more urgent than ever before, with the globe confronting unparalleled environmental issues,. Green technology and innovation are vital catalysts for a future that harmonizes technological progress with ecological conservation. Green technology pertains to the creation and utilization of technologies that enhance environmental sustainability by reducing pollution, preserving natural resources and promoting clean energy (Panwar et al., 2011). Through innovative methods, these technologies seek to lessen the negative effects of human actions on Earth. Advances in green technology help lower carbon footprints while also enabling the development of renewable energy sources, effective waste management systems and sustainable manufacturing practices (Omer, 2008; Zafar et al., 2021). With increasing global consciousness regarding climate change, resource depletion and environmental decline, the role of green technology becomes central in transforming industries, promoting economic growth and securing a robust, healthy ecosystem for future generations. As indicated by its name, 'Green Technology' involves environmentally friendly energy, health and safety concerns that fulfil a 'green' objective (M. Guo et al., 2020). Green technology and innovation involves applying environmental science expertise to safeguard natural resources and the environment. At present, higher education is becoming a crucial avenue for fostering environmental sustainability awareness among students and scholars (Aleixo et al., 2018; Chasokela, 2024). Green Technology and Innovation are the sole means to guarantee a healthier, safer and cleaner planet for future generations. We must consider the future generations and the Green Education Programs will help achieve this. Preservation and sustainability should be included in our educational curricula (Abo-Khalil, 2024). The green training initiative appears to be the sole method for future generations appears to be the sole method for future generations to develop or raise awareness. To promote

sustainability and improve life for future generations, the connection between communities and educational institutions can be developed. This paper explores how green technology aids in creating an environmentally friendly setting that primarily emphasizes the idea of 'GO GREEN'.

Innovation and technology that goes 'green'

Green technology focuses on the development and use of technologies that reduce environmental impacts, for sustainable purposes. It includes renewable energy, sustainable agriculture, waste management and ecological construction. The goal is to minimize pollution, conserve resources, reduce energy consumption and solve problems such as climate change and exhausted depletion**.** Green technology and innovation are pivotal in shaping a more sustainable future. Green technology emphasizes practical, eco-friendly solutions, while green innovation fosters the ongoing development and application of novel ideas and technologies to tackle the ever-changing environmental challenges. Together, they lay the groundwork for building a sustainable world that harmonizes environmental, economic, and social well-being.

The Evolution of Green Technology

Green Technology has a much longer than most people realize, dating back to Great Depression. In reaction to the devastating Dust Bowl of the 1930s, the United States took a crucial step toward environmental stewardship by implementing the Soil Conservation Act on April 27, 1935. This legislation resulting in the establishment of the Soil Conservation Service, a ground breaking program aimed at tackling the extensive devastation caused by soil erosion, which had been compounded by bad agricultural methods and the excessive use of heavy machinery. The Dust Bowl, characterized by continuous dust storms, underlined the critical need for sustainable farming practices and improved land management (Omer, 2008). The environmental movement began to get a place in the early 20th century, initially focusing on the battle against the impacts of industrialization, agriculture, and urbanization on natural resources. The first efforts, such as the Soil Conservation Service, aimed at land management and prevent soil erosion while improving public health and reducing the risk of floods (Robalino, 2007). When the understanding of environmental issues has been deeply dug, it is clear that the actions are more complete than needed to treat the broader impact of human activity for ecosystems.

The field of green technology is vibrant and varied today, with a wide range of creative approaches meant to solve the urgent environmental issues of our day. There are numerous options for lowering our carbon footprint, ranging

from advanced energy storage systems and smart grid technology to renewable energy. Green technologies are also vital in advancing electric vehicles, energy-efficient buildings, and water purification systems—each of which contributes to the larger objective of fostering a more sustainable and environmentally conscious society. Electric vehicles, energy-efficient buildings and water purification all benefit from green technology, which promotes sustainability and reduces pollution (Barba-Gutiérrez et al., 2008). As people become more aware of environmental challenges, there is a greater demand for green technology, which is transforming sectors, creating jobs and encouraging circular economy. Green technology is changing the global economy while combatting climate change by reducing dependency on fossil fuels and increasing resource efficiency. Its ongoing progress provides chances to protect the environment and promote future generation well-being, paving the path for a cleaner, greener and most sustainable future (Brodny & Tutak, 2022).

Four pillars of Green Technology and Innovation

Green technology and innovation encourages sustainable development environmental damage while boosting economic growth and societal well-being. It addresses global issues like as climate change and resource depletion through four primary pillars: Environmental, Social, Economic and Energy Harvesting. These pillars lay the groundwork for a greener, more sustainable future.

1. **Environmental Pillar**: It addresses climate change, resource depletion and habitat loss. Ensuring ecological balance promotes stability, equity and ethical development (Li et al., 2020).
2. **Social Pillar**: It encourages awareness and collaboration to improve healthcare, housing, education and food security. Strengthening social infrastructure improves well-being and promotes long-term economic activity (Duić et al., 2015).
3. **Economic Pillar**: The pillar focuses on sustainable growth and diversification by attracting innovation industries and skilled professionals. It promotes job development, boosts the economy and creates strong communities (R. Guo et al., 2020).
4. **Energy Harvesting**: Energy harvesting represents a pivotal aspect of green technology, leveraging innovative methods to convert waste by-products into usable energy. It minimizes waste, making it an efficient and cost-effective solution for developing economies. By optimising energy use, energy harvesting accelerates the shift toward sustainable practices and greener living (R. Guo et al., 2020).

Strategies of Green Technology

Businesses are increasingly concentrating on implementing green technologies in today's quickly changing market, not only as a need, but also as a strategic advantage to maintain competitiveness and promote sustainable growth. Green Innovation is crucial in developing a successful green technology strategy. Business may stay ahead of the competition by investing continuously in research and development to identify innovative sustainable solutions.

1. Adoption of Renewable Energy: Transitioning to sources such as solar, wind, hydro, and others helps reduce carbon emissions and lessen reliance on fossil fuels. To ensure a more sustainable energy future, governments can invest in large-scale renewable projects, while businesses and households can adopt solar panels or harness wind energy.

2. Eco-friendly Transportation: Air pollution and the consumption of fossil fuels can be decreased by switching to electric vehicles (EVs), increasing public transportation and encouraging walking and bicycling. Promoting carpooling and remote work also reduces emissions from everyday journeys (Kuzey et al., 2022; Punitham & Udhaya Jothi, 2025).

3. Recycling and Water Reduction: Waste is reduced by using a circular economy strategy, which reuses, reduces and recycles items. To limit their influences on the environment, businesses and customers should recycle e-waste, compost organic trash and reduce the usage of single-use plastics (Sala & Serra, 2004).

4. Water Conservation: For sustainability, effective water management is essential. Particularly in areas where water is scare, conserving freshwater resources can be achieved by installing water-saving fixtures, collecting rainfall and recycling wastewater (Beekman, 1998; Klemeš, 2012).

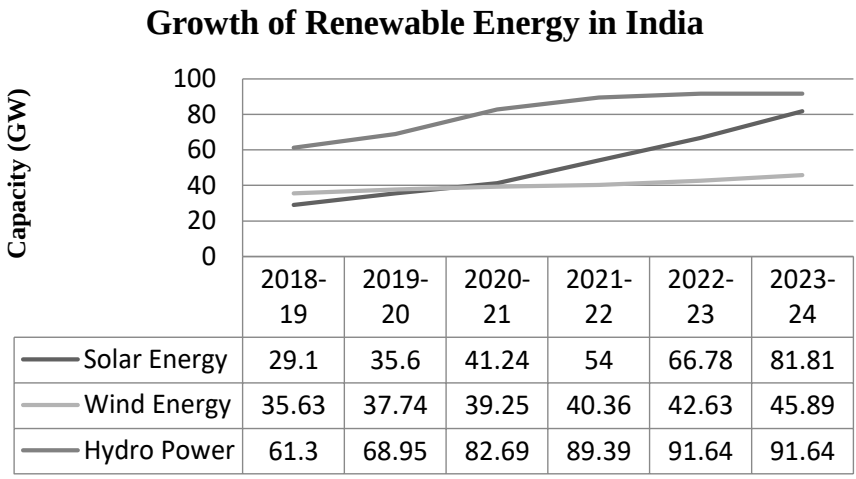
5. Urban Planning and Green building: Heat is decreased and air quality is improved by incorporating green spaces into urban areas and developing energy-efficient structures out of sustainable materials. Sustainable living and resources optimization are two benefits of smart city development (Huo et al., 2017).

6. Environment Policies and Efforts: Through laws, tax breaks and corporate social responsibility efforts, governments and corporations can promote green activities. Policies that promote sustainable behaviours play a key role in encouraging the broader adoption of environmentally friendly technologies (Konisky & Woods, 2012; Robalino, 2007).

Green Technology and Innovation in India

India is quickly adopting green technologies to achieve a balance between environmental sustainability and economic growth. To lower carbon footprints and advance sustainability, a number of industries, including manufacturing transportation, energy and agriculture, are adopting creative solutions.

1. Renewable Energy Growth: India is one of the most rapidly expanding renewable energy sectors, with considerable investments in solar, wind and hydropower. The government intends to attain 500 GW of non-fossil fuel capacity by 2030 and net-zero emissions by 2070 (García Bermejo, 2023; Panwar et al., 2011).



	2018-19	2019-20	2020-21	2021-22	2022-23	2023-24
Solar Energy	29.1	35.6	41.24	54	66.78	81.81
Wind Energy	35.63	37.74	39.25	40.36	42.63	45.89
Hydro Power	61.3	68.95	82.69	89.39	91.64	91.64

Figure 1: Growth in capacity generation of renewable energy in India from 2018 to 2024

The graph illustrates India's solar and wind energy industries' explosive expansion. Government programs like the PM-KUSUM scheme and expansive solar parks have contributed to the notable growth of solar energy (*Impact Analysis of PM KUSUM Scheme Individual Pump Solar Component C*, n.d.).

2. Electrical Vehicles (EVs) and Sustainable Transportation

With programs like FAME II and domestic battery manufacturing, India is advancing electrical mobility. By 2030, the government wants 30% of all automobiles to be electric.

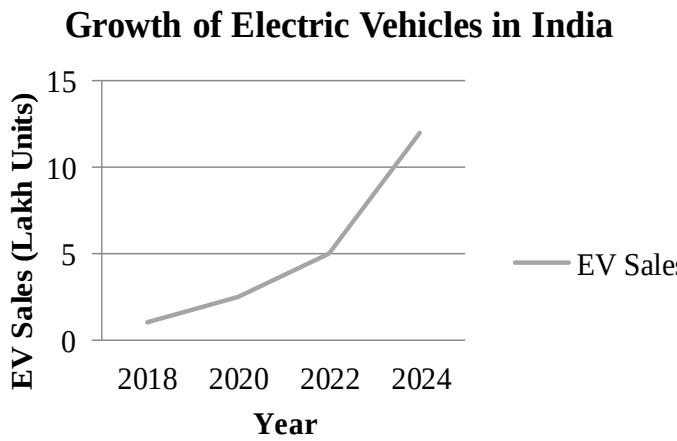


Figure 2: Electric vehicle sales trend in India from 2018 to 2024

3. Waste Management and Circular Economy

India is concentrating on a circular economy and waste management in order to lower pollution and advance sustainability.

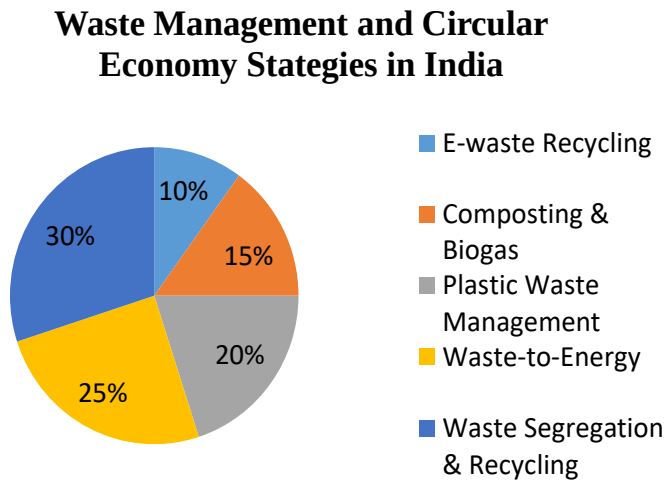


Figure 3: Waste management and circular economy strategies

Case Study of Green Technology

1. Nestlé – Eco-Friendly Packaging: Nestlé, one of the world's largest food companies, has embraced sustainable packaging methods to reduce plastic waste and promote the circular economy. The company aims to make all of its packaging recyclable or reusable by 2025. (Nestlé, 2020).

- Created packaging materials that are plant-based and biodegradable.

- Single-use plastics have decreased in global supply chains.
- Partnered with authorities to enhance the handling of plastic garbage.

2. Tesla – Transforming Electric Vehicles and Energy Storage: Tesla, Inc. has played a crucial role in the electric vehicle (EV) revolution by decreasing reliance on coal and hydrocarbons. The Tesla Powerwall and Megapack, two of the company's lithium-ion battery storage inventions, offer effective energy solutions for homes and businesses. (Musk, 2021).

- Launched long range EV's with zero tailpipe emissions.
- Develop solar-powered energy storage solutions.
- Decreased reliance on fossil fuels.

3. Ørsted – Offshore Wind Energy: Ørsted is a Danish multinational energy firm that transformed from a coal-based energy supplier to a 100% renewable energy company by 2025, supplying sustainable power to millions of homes (Rendtorff, 2023).

- Constructed Hornsea One, the biggest offshore wind farm in the world.
- Decreased reliance on coal for electricity generation by 96%.
- By 2025, plans to achieve carbon neutrality.

4. Indian Railways: Transition to Renewable Energy: Indian Railways has made a major commitment to sustainability by aiming to achieve net-zero carbon emissions and 100% electrification by 2030. This initiative will decrease the use of solar and wind energy. (Indian Railways, 2023).

- Installed solar panels on train rooftops and stations.
- Developed wind farms to power railways operations.
- Introduced hydrogen-powered trains.

Government Initiatives and Policies

To encourage the creation and application of green technologies, the Indian government has proposed many programs, some of which are being discussed below:

- **National Action Plan on Climate Change (NAPCC)**: NAPCC outlines India's strategy to combating climate changes, emphasizing sustainable development, renewable energy and energy efficiency
- **Atal Mission for Rejuvenation and Urban Transformation (AMRUT)**: Through the integration of green technologies into waste

management, water supply and energy efficiency systems, this program supports sustainable urban infrastructure.

- **Make in India**: The *Make in India* initiative promotes the production of green technologies in the country, especially in fields like renewable energy, electric vehicles and energy-efficient appliances.
- **Start-up India**: This program helps green tech start up by giving them access to capital, infrastructure, and government incentives for sustainable agriculture, waste management and clean energy innovation.

India's green technology and innovation challenges and possibilities

Although India is making great progress in embracing green technology and innovation, a number of obstacles must be overcome before the full promise of sustainable development can be realised. These difficulties do, however, also offer a wealth of chances for development and creativity in several fields.

Challenges:

- **High Initial Costs**: Businesses and individuals find it challenging to embrace green technologies since they frequently demand a large upfront expenditure.
- **Infrastructure Gaps**: The growth of green technology is constrained by inadequate infrastructure, such as EV charging stations and unstable power grids.
- **Lack of Awareness**: Adoption of green technologies is slowed by limited consumer knowledge, especially in rural regions.
- **Regulatory Uncertainty**: Varying laws and incentives could discourage investment and impede the development of green technologies.
- Possibilities:
- **Job Creation**: Green technology initiatives can create new jobs, especially in renewable energy, electric mobility, and sustainable agriculture.
- **Global Market Expansion**: India can capitalize on the growing global demand for green technologies, enhancing its competitiveness.
- **Health Benefits**: Reducing pollution through green technologies will lead to better health and reduced burden of the healthcare system.

- **Government Support**: Initiatives like *Make in India* and *Start-up India* offer financial incentives and policy support for green technology businesses.

Emerging Trends and Future Prospects of Green Technology

As green technology transforms industries and spurs innovation for a cleaner future, it is in the front of global sustainability efforts. These developments are changing how we interact with the environment, from innovations in renewable energy to sustainable urban planning.

- **Development in the Production of Green Hydrogen:** In order to produce green hydrogen, researchers have created ultra-efficient electrolysers that achieve 95% efficiency, greatly lowering energy waste (Simhadri et al., 2023).
- **Manufacturing of Clean Energy Powered by Industrial Policy:** In an effort to improve energy security and generate employment, governments are enacting laws to increase the production of clean technologies domestically (Bajra & Čadež, 2020).
- **Prioritize research and development:** Higher research and development expenditures are fostering technological advancements in sustainable energy, increasing productivity and reduces costs (Abo-Khalil, 2024; Chasokela, 2024).
- **Circular waste management and upcycling:** A circular economy is being promoted by creative waste management techniques like upcycling, which transform waste into useful resources (Barba-Gutiérrez et al., 2008).
- **Using Climate Predictive Data:** Businesses and Governments are using predicted climate data to help them make well informed decisions about sustainability and environmental impact (Espinoza & Aronczyk, 2021).

Conclusion

Addressing global environmental issues such as climate change, resource depletion, and pollution heavily relies on green technology and innovation. Green technology creates new prospects for economic growth by producing jobs in developing areas like clean energy, electric mobility, and sustainable manufacturing. As countries work to reach their climate goals, green technology becomes an increasingly important instrument for minimising the negative effects of human activities on the earth. In the Indian context, green technology holds immense potential for transforming the country's

development trajectory. As India experiences rapid economic growth, industrialization, and urbanization, it grapples with serious environmental issues such as pollution, water shortages, and escalating energy needs. Green technologies provide effective solutions to these problems, ranging from renewable energy initiatives like solar and wind power to advancements in energy efficiency, electric vehicles, and waste management. As India continues to prioritize green technology and innovation, it can set an example for other developing nations, demonstrating that economic growth and environmental sustainability can go hand in hand. Through continued investment, research, and policy support, India has the potential to not only overcome its environmental challenges but also harness the economic and social benefits of green technologies for a more sustainable and prosperous future.

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CHAPTER-05

INDOOR AIR POLLUTION AND ITS MITIGATION THROUGH INDOOR AIR PURIFYING PLANTS: A SUSTAINABLE APPROACH

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Abstract

Indoor air pollution, a significant contributor to adverse health effects, has been linked to respiratory issues, including asthma, the most prevalent chronic illness among urban children. Conventional remediation technologies such as HEPA filters and air purifiers can mitigate pollutants but are costly and ineffective against certain contaminants, sometimes exacerbating indoor air quality issues. This article explores cost-effective, eco-friendly bioremediation methods, emphasizing the role of plants in improving indoor air quality. Indoor pollutants, including volatile organic compounds (VOCs), particulate matter (PM), carbon monoxide, nitrogen dioxide, asbestos, lead, phthalates, ozone, pesticides, and perfluoroalkyl substances (PFAS), pose significant health risks. These substances originate from everyday products, building materials, and biological sources, contributing to respiratory and systemic illnesses. Plants, through phytoremediation processes such as phyto-stabilization, phytoextraction, phytodegradation, rhizofiltration, and phytovolatilization, can effectively filter air pollutants. Studies reveal that plants enhance indoor air quality by absorbing VOCs, carbon dioxide, and particulate matter while regulating humidity levels. Plants like spider plants, snake plants, peace lilies, Aloe vera, Boston ferns, and Areca palms are particularly effective in removing harmful toxins, including formaldehyde, benzene, and xylene. This chapter underscores the importance of incorporating plants into indoor environments as a sustainable and natural solution for air purification. Plants act as natural air purifiers by breaking down and trapping toxins, promoting human well-being while preserving the harmony

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of ecosystems. Further research and widespread adoption of indoor plantation strategies could offer significant benefits in mitigating indoor air pollution.

Keywords: Indoor Air Pollution; Air Purifying Plants; Sustainability; Mitigation.

Introduction

Today air pollution especially poor indoor air quality has been associated with adverse effects on human health. Asthma has become widespread across multiple age groups and is now regarded as the most common chronic illness among children living in urban areas (Anandan et al., 2010). Indoor air filtration is a part of a comprehensive approach to enhance respiratory health. Various physicochemical methods and science-based technologies have been effectively used to reduce indoor air pollution (Supreeth, 2021). Air cleaners equipped with HEPA filters have been found to alleviate asthma symptoms. However, filtration systems and air purifiers are not effective at reducing all indoor air pollutants, and certain types can even worsen the situation. For instance, a study found that some air purifiers can increase indoor ozone levels beyond the safety limits set by the U.S. Environmental Protection Agency (Britigan et al., 2006). Due to high maintenance cost of the above-mentioned conventional remediation technologies need to be replaced by more cost-effective, eco-friendly, and non-invasive bioremediation approaches. Biological remediation uses plants and microbes to break down or transform toxic pollutants into non-toxic forms (Supreeth, 2021). A NASA study conducted in space shuttles in the 1980s successfully demonstrated the role of plants in removing airborne pollutants (Wolverton et al., 1989; Chen et al., 2010). Beyond their basic role in photosynthesis, which removes carbon dioxide and releases oxygen, plants can also eliminate toxins from the air, soil, and water in at least two ways. First, they can metabolize certain toxic chemicals, releasing harmless by-products, and second, they can absorb toxic substances like heavy metals into their tissues, effectively immobilizing them.

Indoor environments, especially houses are contaminated by a variety of chemicals, some of which can be harmful to human health when present in high concentrations or over long periods. These chemicals come from everyday household products, building materials, furniture, and appliances.

Common Indoor Chemicals and Their Sources

(a) Volatile Organic Compounds (VOCs).

Volatile organic compounds (VOCs) have a high vapor pressure and low boiling point at room temperature, leading to the evaporation of a significant number of molecules into the surrounding. VOCs are carbon-based

compounds that engage in atmospheric photochemical reactions, excluding carbon monoxide, carbon dioxide, carbonates, carbonic acid, and ammonium carbonate (Gan et al., 2022). These include formaldehyde, Benzene, Toluene and Xylene. Formaldehyde is found in pressed wood products, furniture, and textiles. Benzene occurs in tobacco smoke, stored fuels, and some household products, and toluene is found in paints, paint thinners, and adhesives.

VOCs can cause headaches, dizziness, nausea, irritation of the eyes and respiratory tract, and in severe cases, long-term exposure can lead to cancer or damage to the liver and kidneys air (Wei et al., 2017).

(b) Particulate Matter (PM)

Particulate matter (PM) consists of liquid droplets and solid particles suspended in the air, varying in shape, size, origin, and chemical composition, with many posing health hazards. It comes from Combustion from stoves, fireplaces, tobacco smoke, and outdoor air that come indoors. It can be of two types depending upon size. (1) PM 2.5: Fine particles smaller than 2.5 microns (2) PM 10: Coarse particles between 2.5 and 10 microns. Particulate matter penetrates the lungs and bloodstream, causing respiratory and cardiovascular problems and severe allergic conditions like asthma (Yadav & Devi, 2019).

(c) Carbon Monoxide (CO)

It is a colourless, odourless, non-irritating but harmful gas. It is emitted from incomplete combustion of carbon-containing fuels such as natural gas, gasoline, or wood. It makes up 50% of the total air pollution. Indoor CO comes from improperly vented furnaces, boilers, water heaters, charcoal grills, gas dryers, Tobacco smoke, kerosene or propane space heaters and gas stoves can produce CO. Running generators indoors or in poorly ventilated areas can emit dangerous levels of CO. Running a car inside a closed garage can quickly lead to CO accumulation. Exposure to high levels of CO can cause dizziness, confusion, unconsciousness, and even death due to the reduction of oxygen in the bloodstream. CO competes with oxygen for the same binding site in the iron (Fe^{2+}) of haemoglobin. When haemoglobin binds with CO (forming carboxyhaemoglobin), it can no longer transport oxygen. Haemoglobin's affinity for CO is 210 times greater than for oxygen, which explains CO's extreme toxicity even at low concentrations in the air. For example, inhaling air containing 0.02% CO for two hours can cause symptoms like headaches and nausea. At a concentration of 0.1%, CO can lead to unconsciousness within an hour and death from asphyxiation within four hours (Salthammer, 2024).

(d) Nitrogen Dioxide (NO_2)

It comes from gas stoves, space heaters, Indoor kerosene lamps and tobacco smoke. NO_2 can react with moisture in the air or on the skin to form nitric acid (HNO_3). Nitric acid is highly corrosive and can cause skin irritation or burns upon contact. Exposure to NO_2 can also cause respiratory irritation, particularly in the eyes, nose, and throat, leading to symptoms such as coughing and shortness of breath (Bernstein et al., 2008).

(e) Asbestos

It is released from vinyl tiles, vinyl sheet flooring, acoustic ceiling tiles, fire-resistant drywalls, fireproofing materials, adhesives used for flooring tiles, and roofing materials. Older fireproof blankets, curtains, and certain sealants may also contain asbestos. Asbestos becomes hazardous when it is disturbed, releasing fibers into the air that can be inhaled. If a home contains materials with asbestos, it's important to avoid disturbing them and seek professional help for removal or repair. Prolonged exposure can cause lung diseases such as asbestosis and mesothelioma. Prolonged exposure can cause lung diseases such as asbestosis (Kim et al., 2017).

(f) Lead

It comes into the environment from older paints, contaminated dust, water from lead pipes, and plumbing materials. It is dangerous for children; it can cause developmental issues, learning disabilities, and neurological damage. It is carcinogenic in nature. Lead interferes with haemoglobin production, leading to anaemia. It can weaken the immune system, making the body more susceptible to infections. In pregnant women, lead exposure can result in miscarriage, premature birth, and low birth weight. It may also cause infertility in both men and women. Chronic lead exposure can lead to kidney damage and impair kidney function. Prevention includes eliminating lead sources and maintaining good hygiene, like regular cleaning to reduce dust (Tan et al., 2016).

(g) Phthalates

These are a group of commonly used chemicals in plastics, vinyl flooring, wall coverings, and personal care products. These are known to act as endocrine disruptors, posing significant risks to human health. Although they have short half-lives in tissues, prolonged exposure to phthalates can have detrimental effects on the endocrine system and the function of various organs. This chronic exposure can lead to long-term health issues, including negative impacts on pregnancy outcomes, child growth and development, and

the reproductive systems of both children and adolescents (Wang & Qian, 2021).

(h) Ozone (O_3)

Indoor O_3 is generated by certain air purifiers and photocopiers. It can cause lung irritation, worsen asthma, and decrease lung function over time. Low levels of outdoor ozone exposure have been linked to harmful effects on respiratory health. However, studies conducted in controlled settings show that much higher ozone levels are needed to observe these effects, and the reason for this difference is not well understood. When ozone enters indoor spaces, a significant portion reacts with indoor chemicals, creating byproducts that may be more harmful than ozone itself. To test this, a study conducted with 70 healthy adults supported the idea that indoor ozone reaction byproducts play a significant role in the respiratory issues caused by outdoor ozone exposure (He et al., 2025).

(i) Polybrominated Diphenyl Ethers

Polybrominated diphenyl ethers (PBDEs) are flame retardants commonly used in materials such as plastics, textiles, and polyurethane foam. Structurally, they consist of two halogenated aromatic rings linked by an ether bond and are categorized based on the number and position of bromine atoms. Due to their extensive use, PBDEs have been detected in various environmental media, including soil, air, water, and dust, as well as in animal tissues. Additionally, PBDEs have been identified in human tissues such as the liver, kidneys, adipose tissue, brain, breast milk, and plasma. The persistent accumulation of PBDEs has raised significant concerns regarding their potential toxicity, which includes hepatotoxicity, nephrotoxicity, gut toxicity, thyroid toxicity, embryo toxicity, reproductive toxicity, neurotoxicity, and immunotoxicity (Xue et al., 2023).

(j) Pesticides

Pesticides are commonly used to manage weeds, insect infestations in agricultural settings, and various pests and disease carriers such as mosquitoes, ticks, rats, and mice in residential, commercial, and public areas. However, because pesticide modes of action are not specific to particular species, there are significant concerns about environmental risks associated with exposure through various pathways, including residues in food and drinking water. These hazards can range from short-term effects, such as skin and eye irritation, headaches, dizziness, and nausea, to long-term impacts, including cancer, asthma, and diabetes (Xue et al., 2017).

(k) Perfluoroalkyl And Polyfluoroalkyl Substances (PFAS)

(PFAS) are a diverse group of over 4,000 man-made chemicals that have been utilized in consumer products globally since around the 1950s. These substances are found in various everyday items, such as non-stick cookware, stain-resistant fabrics and carpets, cleaning products and highly effective firefighting foam. PFAS molecules consist of a chain of interconnected carbon and fluorine atoms. Due to the strength of the carbon-fluorine bond, these chemicals resist degradation in the environment, making them persistent pollutants. PFAS exposure is linked to several health impacts like immune dysfunction particularly in children, Dyslipidemia, and nervous developmental issues (Sunderland et al., 2019).

Moreover, some harmful indoor pollutants originate from biological sources, including pollen, animals, pathogens, water vapour, humidifiers, air conditioning systems, and carpets (De Gennaro et al., 2014).

Mitigation Of Indoor Air Contamination Through Indoor Plantation

Plants serve as an effective cleaning system for the environment through a process called "phytoremediation." This involves various techniques where plants remove pollutants from the environment. Indoor plants act as natural air filters, purifying the air through various mechanisms such as absorption, dilution, precipitation, and filtration. One of the most well-known processes they perform is photosynthesis, where plants clean the air by taking in carbon dioxide and releasing oxygen. Another process, respiration, involves plants absorbing oxygen and releasing carbon dioxide. During these processes, air passes in and out through the stomata, which are key structures involved in plants' absorption and filtration mechanisms (Jones, 1998).

Phytoremediation encompasses various techniques employed by plants to remediate contaminated environments. These techniques can be categorized into five primary areas:

- **Phyto-Stabilization**: This involves the immobilization of contaminants in the soil, reducing their bioavailability and minimizing the risk of leaching into water or dispersing into the air (Morikawa & Erkin, 2003).
- **Phytoextraction**: This process entails the uptake and accumulation of pollutants by plants, effectively removing contaminants from the soil (Lee, 2013).

- **Phytodegradation**: In this method, toxic pollutants are transformed into less harmful or non-toxic substances through the metabolic activities of plants (Lee, 2013).
- **Rhizofiltration (Phytofiltration)**: This technique uses plant roots (rhizofiltration), shoots (caulofiltration), or seedlings (blastofiltration) to remove pollutants from water or wastewater (Yan et a., 2020).
- **Phytovolatilization**: Here, plants take up volatile toxic elements from the soil, convert them into less toxic forms, and release them into the air via transpiration through their leaves (Mahar et al., 2016).

Plants can absorb airborne molecules and contribute to restoring ecological balance in the air (Agarwal et al., 2019). They also help remove pollutants such as carbon dioxide, volatile organic compounds (VOCs), carbonyls, particulate matter, organic compounds, nitrates, sulphates, ammonia, calcium, ozone, and carbonate. As a cost-effective solution, indoor plants significantly reduce indoor pollutant levels and minimize human exposure to harmful substances (Soreanu et al., 2013; Parseh et al., 2018; Wei et al., 2017).

Indoor relative humidity (RH) plays a crucial role in the interaction between humans, microorganisms and plants. Ideal indoor humidity levels for human comfort typically range between 30% and 60% (Fan et al., 2017), with 40–60% being particularly effective in reducing infections (Audi et al., 2020). Studies have shown that plants can absorb tiny airborne water vapour particles, thereby improving indoor humidity levels (Pérez-Urrestarazu et al., 2016). Although concerns have been raised about indoor plants releasing water droplets into the air through transpiration, leading to increased humidity, plants naturally regulate this process. At higher humidity levels, the transpiration rate decreases, maintaining indoor humidity within a comfortable range for humans (Pegas et al., 2012). Studies are available providing evidence that plants can reduce fine particles in the indoor environment. Stapleton evaluated 11 different household plant species and found a significant reduction in ultrafine particles (Stapleton & Ruiz-Rudolph, 2018).

Some popular and effective indoor plants that purify the air and improve air quality by filtering out toxins ate enlisted in Table -1.

Table -1

Sr.No	Name of Plant (Common Name)	Pollutants adsorbed by plants	References
1.	*Chlorophytum comosum* (Spider Plant)	particulate matter, carbon monoxide, formaldehyde, xylene	Gawrońska & Bakera, 2015
2.	*Sansevieria trifasciata* (Snake Plant)	Formaldehyde, xylene, benzene, toluene, and trichloroethylene	Sharma et al., 2018;
3.	*Spathiphyllum* (Peace Lily)	Ammonia, benzene, formaldehyde, and trichloroethylene	Pamonpol et al., 2020
4.	*Aloe vera* (Ghrit Kumari)	Formaldehyde and benzene	Ghate, 2020; Parseh et al., 2018
5.	*Asplenium nidus* (Bird Nest Fern	CO2 and Formaldehyde	Shishegaran et al., 2020
6.	*Dypsis lutescens* (Areca Palm)	Total volatile organic compounds (TVOCs), carbon dioxide (CO2), and carbon monoxide (CO)	Su & Lin, 2015
7.	*Hedera helix* (English Ivy)	Formaldehyde formaldehyde, benzene, trichloroethylene, and carbon monoxide	(Bhargava et al., 2021).
8.	*Chamaedorea seifrizii* (Bamboo Palm or Reed Palm)	formaldehyde, benzene, trichloroethylene, and xylene	Hwa Yoo et al., 2006; Wolverton, 1993
9.	*Dracaena marginata* (Madagascar Dragon Tree)	Toluene, Xylene and Formaldehyde	Teiri et al., 2021

10.	*Phoenix roebelenii* (Dwarf date palm)	Toluene and xylene	Teiri et al., 2021
11.	*Nephrolepis exaltata* (Boston fern)	xylene, toluene and formaldehyde	Wolverton, 1993
12.	*Liriope spicata* (Lily turf)	benzene, xylene, toluene and formaldehyde	Wolverton, 1993
13.	*Epipremnum aureum* (Money Plant)	toluene, xylene, toluene and formaldehyde, ammonia, hydrocarbons	Wolverton, 1993
14.	*Anthurium andraeanum* (Flamingo lily)	Benzene, toluene, xylene, formaldehyde.	Papinchak et al., 2009
15.	*Chrysanthemum morifolium* (Florist's Chrysanthemum)	trichloroethylene and ammonia	Wolverton, 1993

Conclusion

In conclusion we can say that Indoor air pollution poses significant health risks, emphasizing the need for sustainable solutions. Conventional methods like HEPA filters are effective but limited by cost and scope. Incorporating indoor plants offers a cost-effective, eco-friendly alternative for mitigating air pollution. Plants not only enhance aesthetics but also purify air through phytoremediation processes, absorbing harmful toxins, VOCs, and particulate matter while regulating humidity. Species like spider plants, snake plants, and peace lilies demonstrate exceptional air-purifying abilities. Leveraging indoor plants as natural air filters promotes healthier living environments, supports ecological balance, and emphasizes the significance of incorporating eco-friendly solutions into urban living environments.

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CHAPTER-06

CLIMATE CHANGE POLITICS: UNDERSTANDING THE INTERSECTION OF SCIENCE, POLICY AND POWER

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Abstract

Climate change has become one of the most important issue in the scientific, financial as well as political circles. This study explores interdependence between science, policy and power, examining the ways in which these factors interact and impact climate governance. Undoubtedly, there is a startling discrepancy among the opinion between climate threats as well as the steps being implemented to reduce and prepare for climate change. First, we understand that decisions are never made only based on facts. Weighing costs, benefits and risks all of which are distributed differently around the world is necessary when making decisions. Values are involved in making trade-offs. Therefore, in order to take action, value conflicts and discrepancies must be overcome. Second, climate policy invariably encompasses a wide range of topics and interested and impacted parties. Even when facts and ideals are agreed upon, procedures can still be slowed down by that complexity alone. However, a particularly concerning roadblock to climate action is deliberate rejection of scientific consensus by certain elites and elements of the public. It asserts that a thorough comprehension of these connections is essential for creating efficiency.

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Keywords: Climate, Governance, Climate Risks, Sustainable Development.

Introduction

A complex and multidimensional issue, climate change (CC) has social, political, economic, and scientific facets. Regarding CC, the scientific community reports the burning of fossil fuels and reduction in number of trees as a major cause of emissions, leading to global warming and its related effects (Dhillon & Wuehlisch, 2013). Notwithstanding this consensus among scientists, the politics always accompanies the controversies, inaction, and delay.

Environmental protection is indeed a top priority for many countries these days. They are actively working to develop legislation that can lower greenhouse gas emissions because they are worried about the serious harm that CC may do in the near future. But in spite of heightened awareness and heated debates, governments' environmental policies are typically less aggressive than what they had promised and fall well short of meeting their long-term climate goals. According to a recent UNEP assessment (Depledge et al., 2022) half of the G20 nations, including the US are unlikely to fulfil their initial obligations under the Paris Agreement under the policies now in place.

The term "climate change politics" refers to changes in climate and its annual cycles as real phenomena and to describe its current and projected effects on the environment as well as the broader ramifications for human activity in order to inform political action. Developing a suitable political response requires a precise understanding of the causes, scope, timescale, and consequences of such a rapid change. The politics around CC have proven to be quite controversial; both domestically and internationally because of the serious concerns connected to its effects and the distributional effects of measures meant to mitigate them.

In the administration of CC, the interdependence between science and legal policymaking is crucial, yet frequently problematic. Scientists offer vital information about climate threats, causes and remedies but political and economic interests usually get in the way of turning this information into policy. Policymakers may disregard unfavourable results, take advantage of uncertainty to postpone action or selectively use scientific facts to supports pre-existing agendas. Furthermore, policymakers are sluggish and controversial due to the complexity of climate challenges, which impact numerous sectors and stakeholders. This dynamic is further complicated by the influence of corporate interests. Stronger communication between

scientists and policymakers increased decision making, transparency and safeguards integrity are all necessary for effective climate governance (Hulme, 2009).

Conflicts due to climate change

Although it frequently occurs indirectly, CC does play a role in the rise of conflict. The most vulnerable become even more exposed as a result. When it comes to UNHCR's work, we see that no group is more at risk than those who have been forced to leave their country because of violence and are currently experiencing the consequences of a hostile environment. It is also becoming increasingly doubtful that those who have lost their homes due to wars, and environmental degradation will be able to return home.

Vulnerable regions are disproportionately affected by CC, especially those with little adaptive capacity. The repercussion is severe and includes food insecurity, water scarcity and displacement for marginalised population, law income communities and fragile state. According to the UNHCR, ninety per cent of the refugees worldwide come from nations that are already affected by the climate related calamities like protracted droughts and extreme weathers events. Moreover the UNEP 2021, emissions gap report posits that delayed growth and poor governance increase vulnerability, making it more challenging for these areas to adopt climate adaptations measures. CC wont's to stop unless immediate action is taken.

Vulnerable areas are disproportionately affected by CC because of a confluence of political, social and economic variables. Communities in many developing countries are vulnerable to catastrophic weather events, drought and sea level rise because they lack the infrastructure and financial resources necessary to adopt effective adaptation plans. The resources needed for preparedness and adaptation are frequently lacking in regions. Countries that have poor governance, sluggish development and a lack of social investment in vital sectors like healthcare, education, and the rule of law are unable to devote the necessary funds for environmental preservation. Additionally, these countries are less likely to put preparedness and adaptation plans into action, particularly for underserved communities. In addition to being essential for environmental sustainability, addressing and mitigating CC is also essential for promoting peace and addressing the causes of many conflicts.

International Climate Governance

In the political debate over CC, international climate governance is crucial part of the challenge. The 2015 Paris Agreement (Depledge, 2016) aims to keep the increase in average world temperatures lower than 2°C, with a 1.5°C

kept as target. The agreement's voluntary nature and lack of strong enforcement measures, however, have raised questions about its overall effectiveness.

Climate change politics are heavily influenced by the dynamics of power and vested interests. For example, companies that produce fossil fuels have a strong motivation to maintain the current working conditions and have used their veto power or delay climate efforts (Klein et al., 2022). Similar to this, some governments might put economic expansion ahead of climate action, especially if their economies rely significantly on the export of fossil fuels.

Conflict, displacement and CC interact in complex ways that differ depending on the situation; oversimplifying this relationship could lead to inappropriate or ineffectual responses. Nonetheless, we are going to witness an increase in the conditions that foster conflict and violence unless more money is allocated to helping communities worst implicated by this and improve their capacity to adapt and prepare for the unavoidable increase in extreme weather events. These include persistent droughts in different areas, unpredictable rainfall patterns that cause flooding or drought, risks to food security made worse by the on-going conflict in Ukraine, where Russia and Ukraine are both significant exporters of agricultural commodities, and the pressure on livelihoods that are sensitive to CC, like those of smallholder farmers and pastoralists. In many regions, the rise of non-state entities, particularly militant organizations, can be attributed to governments' failure to uphold their social obligations and deliver basic services.

There aren't many present outcomes. It is possible to mitigate some of the expected consequences by foreseeing future dangers and utilizing sufficient political will. Our rate of action, however, is not fast enough. Africa, Asia and America are the region's worst affected regions, home to between 3.3 and 3.6 billion people. The gap between what is needed and what is now being done for adaptation is growing, especially for lower-income groups. In the absence of prompt, extensive measures to reduce vulnerability in the most impacted communities and countries, we will see a rise in violence, displacement, and misery.

For millions, the situation is becoming more complicated and unpredictable due to a combination of environmental deterioration, locust infestations, droughts, flooding, and poor governance. Even though we don't fully understand the causes of individual or community migration, it's clear that trends like urbanization and the demise of small-scale farming are being exacerbated by a string of catastrophic events across the world, such as Africa as week as Americas' Arid Corridor.

A report by the Internal Displacement Monitoring Centre, harsh weather events caused one individual to be displaced every two weeks over the previous year (Birkeland, 2009). This is especially concerning because the data and the apparent lack of proactive preparedness and adaptation efforts indicate that people are moving to more vulnerable locations, which will inevitably result in a rise in this number. The most recent IPCC report supports mounting evidence that relocation in all regions is increasingly caused by weather and climate extremes.

A major contributing factor to the worldwide food crisis is the ongoing conflict in Ukraine. Fertilizers and other necessary food supplies are supplied by both Russia and Ukraine. The war has caused these commodities' supply networks to break down, which has caused food and fertilizer prices to skyrocket. 36 of the 50 countries that depend on these two countries for more than half of their wheat imports get at least 30% of their wheat from them. Prices for wheat and maize have skyrocketed globally due to expected shortages brought on by Russia's invasion.

Case Studies

A variety of case studies illustrate the complex interrelationships between politics, policymaking and academic research around CC. A few noteworthy instances are:

- The ExxonMobil controversy: In 2015, it was discovered that ExxonMobil had funded efforts that supported climate denial while purposefully concealing scientific facts about CC (Supran & Oreskes, 2017).
- Climate policy during the Trump administration: A strong ideological opposition to climate action and the substantial influence of fossil fuel interests are highlighted by the Trump administration's plan for backing out from the Paris Agreement and to reverse domestic climate efforts
- The European Union's leadership in climate action: The EU has established aggressive climate targets and implemented measures to achieve these goals, positioning itself as a leader in climate action.

The Sahel region's high reliance on food imports is predicted to have a significant impact. Food insecurity in this region, especially among the poor, may worsen due to the looming global food crisis. Staples including rice, wheat, oil, and sugar have already seen local price increases of 20% to 50% in a number of the region's countries. According to projections from the World Food Programme, the violence may cause an additional 7–10 million West Africans to experience food insecurity.

Sudan's civil war is often cited as the first modern conflict driven by climate change. What other conflicts have been indirectly influenced by CC? There is strong evidence that conflict may rise as a result of climate change, mostly through indirect causes. A number of contextual elements, most notably political dynamics, governance, and socioeconomic circumstances, combine to increase the likelihood of conflict related to CC.

Climate change is projected to exacerbate existing trends in India

- **Agriculture:** Crop yields are at risk due to temperature and precipitation changes, which causes food insecurity and rural poverty.
- **Water Resources:** Water security and livelihoods are under risk due to decreased water supply, elevated water demand, and changed water quality.
- **Human Health:** Heat waves, vector-borne diseases, and air pollution pose significant risks to human health.
- **Coastal Areas:** Infrastructure and populations along the shore are under risk from sea level rise and coastal erosion.
- **Biodiversity:** CC threatens biodiversity, including endangered species and ecosystems.

India's Current Climate Change Policy: A Brief History

India has mostly sought to promote synergies between climate results and developmental aims through its climate change policy. In 2001, India became among the select few nations to pass the Energy Conservation Act, which was later revised in Aug-2022. The Energy Conservation Building Code (ECBC) that governs the energy load among offices and housing residencies having energy loads of 100 KW or more, as well as those for ships and automobiles will be established (Tulsyan et al., 2013). Other significant changes include provisions encouraging consumers to use non-fossil sources. India has developed a number of missions and initiatives in this regard that are employed as state mechanisms to govern and control the power consumption. The release of the National Action Plan on Climate Change (NAPCC) took place on 30 June 2008 (Pandve, 2009). Within India's developmental framework, this national strategy's eight sub-missions aim to improve ecological sustainability. The National Mission for Sustainable Agriculture (NMSA) (Singh & Singh, 2024), National Mission for a Green India (GIM) (Jha, 2012), National Mission for Sustainable Habitat (NMSH), National Mission for Water Mission (NWM) (Shrestha & Mishra, 2021), National Mission for Sustaining the Himalayan Ecosystem (NMSHE), National Mission on Strategic Knowledge for Climate Change (NMSKCC), and

National Mission for Enhanced Energy Efficiency (NMEEE) are among the sub-missions.

Keeping a target of reaching net zero emissions by 2070, the updated Nationally Determined Contribution (NDC) for submission to the United Nations Framework Convention on Climate Change (UNFCCC) under the Paris Agreement was adopted by the Union Cabinet, which is chaired by the Prime Minister, on August 3, 2022. The "Panchamrit" (5-nectar ingredients), India's CC strategy, was unveiled during COP-26 in Glasgow, UK (Carter & Pearson, M., 2024).

The following texts, laws, and policies inform India's CC policy:

1. **The National Climate Change Action Plan (NAPCC):** This plan, which was published in 2008, outlines the country's policies and initiatives for mitigating and adapting to CC. It includes eight national missions, including the National Mission for Sustainable Habitat and the National Solar Mission.
2. **Energy Conservation Act:** This law, which was amended in 2022, requires users to supplement their energy requirements using non-conventional sources. In addition, it enforces the Energy Conservation Building Code (ECBC) for commercial and residential and has put up boundary on energy consumption guidelines for automobiles and ships.
3. **NEP2023, the National Electricity Plan for 2023**: A key policies that shapes the nation's energy framework is this document.
4. **National Green Hydrogen Mission:** This document serves as a significant policy framework that influences the energy sector.

India's climate change strategy encompasses:

- The International Solar Alliance and the Coalition for Disaster Resilient Infrastructure (Panwar et al., 2022)
- India's Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC)
- Paris Agreement
- The National Infrastructure Pipeline, which links infrastructure initiatives with potential investors
- Partnerships with the European Investment Bank to assist small and medium-sized enterprises (SMEs) in their sustainability transition.

Current challenges in India's climate policy

The Ministry of Power (MoP) is the main Ministry under the Energy Conservation (Amendment) Bill 2022, and the Bureau of Energy Efficiency (BEE) is the executing agency. Nonetheless, questions have been raised if the MoP is qualified to supervise this project (Dorokhina & Sakharov, 2023). The Ministry of Environment, Forests, and Climate Change (MoEFCC) is in charge of legislation and CC matters, as per the Business Allocation Rules. Programs described in similar legislation are usually administered by the Environment Ministry in countries such as the US and the UK. Furthermore, there is uncertainty surrounding the Act's regulation of carbon credit certificates, and the interchangeability of these certificates is still not well defined, considering that the same action may involve carbon credits, renewable energy, and energy savings.

India's current solar rooftop panel installation total of 6.7 GW15 is well behind its 2022 objective of 40 GW. This leads to a projected 32 GW shortfall in reaching 100 GW as the overall target of solar capabilities by 2021 (Girard et al., 2025). This shortcoming is caused by a number of factors, including inconsistent policies, distribution companies' poor performance, rising tariffs, and promote more large-scale projects on renewable energy, according to the Center for Science and Environment's "The State of Renewable Energy in India 2019" report, which was published in New Delhi. The slow progress is due to the preference for commercial and industrial sectors over residential projects.

Key Recommendations:

The complex interrelationships between science, policy, and power impact CC politics. Comprehending these dynamics is essential to developing climate policies that work and promoting sustainable development. This essay emphasizes the need for:

1. **Improved communication between research and policy:** To guarantee that scientific discoveries are successfully converted into workable legislation, cooperation between scientists and legislators is crucial.
2. **Greater transparency and accountability: A**ccountability for climate-related actions is essential, and building confidence and encouraging accountability require transparency.
3. **Climate justice and equity:** The needs and rights of susceptible groups, such as indigenous peoples and poor communities must be given top priority in climate policies.

4. **India must recognize climate change as risk to its development:** The implementation of the State Action Plan on Climate Change (SAPCC), which supports the National Action Plan on Climate Change (NAPCC) more broadly, should be spearheaded by the states. Chhattisgarh has started a number of cross-sectoral projects in this area, including Bari (backyard farming), Ghurva (compost pits), Garva (livestock), and Narva (rivers and streams). These programs are prime examples of successful state-level climate leadership, as is the health department's objective of reaching net-zero emissions. Forestry, livelihoods, climate-resilient agriculture, and the decarbonization of industry and transportation are among their top priorities.
5. A lack of political will prevents political leaders from making CC a top priority. Understanding that the effects of CC may jeopardize efforts to reduce poverty and promote economic growth is essential. Therefore, measures to increase political motivation for climate concerns should be taken.
6. The successful execution of climate initiatives is hampered by institutional issues. Among the concerned offices, CC knowledge management cells have been developed to solve coordination concerns. Designated nodal officers who can serve as focal points for cooperation across different ministries and departments should be included to these cells.
7. Up until April 2021, upwards of $29 billion have been put in to encourage production as well as consumption at a large scale. The ongoing focus on coal puts attempts to find cleaner energy sources at risk. Electricity distribution systems must be strengthened, and coal must no longer be supported by the public or government.
8. It is important to preserve and improve the natural carbon-rich ecosystems, like wetlands and forests, which can increase agricultural output and absorb carbon dioxide.
9. Development through R&D, initiatives such as the Indo-German Energy Forum (IGEF), which was founded in 2006 to enhance Indo-German cooperation in renewable energy, investment, and research and development in energy projects, must be supported (García Bermejo, 2023).

10. India must increase its use of solar energy. It is important to promote alternatives such as offshore wind and floating solar as well. These have a high energy production and don't require a lot of land. India has to expand its energy storage infrastructure in order to strengthen its non-fossil fuel basis. However, because of the state of the global lithium industry, this is highly dependent on the supply chain for lithium batteries, which is difficult to obtain.
11. Understanding planning capability, determining investment needs, and mobilizing it are the three components of climate investment planning. Based on factors like effect, gender and vulnerability issues, sustainable development potential, and readiness, a sector working group of Jordan's development partners, ministry representatives, and civil society members has determined 35 priority initiatives. In order to close the funding gap, India should take note of this, encourage project creation in its early phases, and help project creators' access appropriate funding possibilities.
12. Developing sector-specific investment and private sector engagement strategies to support Nationally Determined Contributions (NDC), strengthening national sector capacities to secure and manage climate finance, encouraging increased participation of financial and industry leaders in the NDC process (including partnerships and project development), establishing political leadership in partnership with the private sector, and showcasing reciprocal benefits to raise aspirations are some additional actions that India should take.

Conclusion

India was the world's 3rd-largest emitter of greenhouse gasses in 2020. According to climate researchers, India's emissions will not peak by 2030 but rather between 2040 and 2045. The country's energy transformation goals for the latter half of the century may face difficulties as a result of this trajectory. It is crucial to have a forward-thinking and practical approach. To support the nation's objective of boosting its renewable energy capacity, coal which happens to be the largest contributor to India's energy landscape, must be put through regulations in addition to a shift to renewable energy. As carbon sinks, woods need to be managed sustainably, which calls for cooperation

between the people, businesses and the government. The backgrounds in all cases are meant to promote a strong CC policy in India are the financial, political, and policy leadership. For India to meet its energy demands in a way that is climate resilient and achieve sustainable long-term growth, engagement at the various governmental levels is essential. Finally, combating CC necessitates a significant overhaul of our social and economic structures. By comprehending how science, policy, and power interact, we can come up with a greener future for the society.

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CHAPTER-07

REDUCING CARBON FOR A SUSTAINABLE FUTURE

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Abstract

Environmental concern is augmenting these days and there is an imperative need to reduce carbon emissions to mitigate the dilemma of global warming. Greenhouse gas emissions from various sources are increasing day by day and adding to the cause. Carbon footprints in diverse sectors are responsible for the climate change and several other environmental issues. This chapter will focus on the current trends, distribution, impact and challenges of carbon footprints. Carbon footprints from diverse sectors like health, agriculture, tourism, hotel, household, construction materials, seafood industry and heat pumps have been discussed briefly. Carbon footprints of engineering projects like water diversion, desalination projects, sewage treatment methods have also been considered. The study and calculation of carbon footprints from these ventures can act as valuable source for decision making regarding water utilization and conservation. It is our sheer accountability to identify ways to reduce carbon emissions to minimize potential environmental hazards. Several methodologies have been discussed in this chapter which can be helpful for designing low carbon strategies.

Keywords: Carbon emission, Carbon footprints, Climate Change, Environmental issues, Global warming, Low carbon strategies.

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Introduction

Climate change is a major issue in current society as it is further leading to extreme weather conditions like high occurrence of floods, droughts, cyclones, storms and many more disasters. The carbon footprint (CF) has emerged as an important benchmark towards contribution to the climate change. The CF includes emissions from diverse sectors including household as well as industrial units. The actual definition of carbon footprint is still controversial but in a simple language it can be referred to the amount of gaseous emissions from human consumption or production activities that are responsible for the climate change (Ramaswami, 2008) In some articles, carbon footprint has also been defined as a complete measure of the total amount of direct or indirect carbon dioxide emissions caused by some activity or accumulated over the life stages of a product (Peters, 2010). Earlier, only CO_2 is taken under consideration for estimating carbon emissions but now all the other greenhouse gases like CH_4 and N_2O are also taken into consideration.

Carbon Footprint in Various Sectors

Health Sector

Climate change is influencing the health care sector in many different ways. Moreover, climate impact is stressing the already existing health care system. Climatic burdens like floods, droughts, storms, heat waves, infectious outbreaks, food shortages increase the need for healthcare services (Watts et al., 2017) The reduction in meat consumption and change in lifestyle from power-driven transport to active mobility would reduce the carbon footprints from the health sector and also improve the public health (Shaw et al., 2014).

Agriculture Sector

Agriculture sector shares a major part of Greenhouse gas emissions. The abundant increase in population is escalating the demand of food supply that is putting an undue burden on agriculture sector. The increasing use of chemicals, natural resources and fossil fuels and various agricultural activities like irrigation, manuring, tilling, plowing, rearing livestock emit a significant amount of greenhouse gases (Clair et al., 2008). The utilization of fossil fuels is contributing maximally to the GHG emissions. Besides utilization, the production and transportation of fossil fuels also contribute to the GHG emissions. Crop cultivation mainly cereals is majorly contributing towards

GHG emissions. Both pre farm activities like manufacturing of fertilizers, pesticides, fuel, electricity and post farm activities like utilizing electricity, transportation, packaging and trash treatment add to the carbon emissions (Hedayati et al., 2019). Moreover, the increasing conversion of natural ecosystem for agriculture use and the practices like deforestation, excessive use of fertilizers and pesticides, crop residue burning after harvest are significantly adding to the carbon emissions. Various measures like limiting the deforestation, efficient use of fossil fuels and other non renewable resources, helpful agricultural practices like crop rotation system, use of sustainable and organic fertilizers, micro-irrigation methods, pest and disease management techniques may facilitate to reduce the carbon emissions from agriculture sector (Gan et al, 2014).

Livestock sector also contributes towards GHG emissions mainly through transportation, manure application and feed production. Methane is the major GHG emitted from livestock sector. Also, beef and cattle contribute more in carbon footprint than other farm animals. The higher carbon footprint of animal based products like milk, eggs, meat is more than the plant based products due to higher carbon footprint of animal feed (Håkansson, 2022).

Buildings

The commercial and residential buildings along with the use of raw materials to manufacture building products and their further transportation highly contribute to the increasing CFs. The study of CFs from buildings is important to design a tool for reducing carbon footprint from the construction sector and leading it towards more sustainable environment (Fenner et al., 2018). The literature reveals that carbon footprint varies for commercial, educational, household and federal buildings. In recent years, focus is laid on such building materials that are environment friendly. The estimation for building CFs is divided in four stages:

Product Stage

The emissions from this stage are also referred to as embodied emissions. This comprises emissions from the production of building materials including the raw materials, the manufacturing process and their transportation. The emission from this sector varies according to the nature of building material, type of energy source used in the entire process and building lifespan (Chau et al., 2015). The building lifespan has an inverse correlation with the emission data. The steel frame buildings are more energy demanding than the concrete frame buildings. CFCs and HCFCs from non natural refrigerants contribute a lot to the global warming. In recent years, progress has been

made to develop air conditioning systems with better design, low leakages and based on natural refrigerant systems. The selection of materials that are available near the construction site also reduce the carbon emissions by the decline in the transportation cost. The optimum heights of the buildings also reduce the carbon emissions.

Construction stage

This stage includes the activities between the manufacturing and the operational stage like the transportation of materials to the construction site, equipments used for the building purpose and production process. Several factors like the size and the location of the building, energy source used in the construction and transportation process are considered in the construction phase (Guggemos et al., 2005).

Operational stage

This stage accounts for the maximum carbon emissions from the lifestyle of people in society putting an undue burden on the fossil fuels mainly for generation of electricity. The source of energy production, occupation of people and location of buildings affect the amount of carbon emissions. The buildings that mainly rely on renewable sources of energy emit fewer GHG as compared to buildings depending on coal, natural gas and nuclear energy resources. Air conditioning units, use of high power appliances and lightning contribute maximum to the energy consumption (Airaksinen et al., 2011). The emissions coming from the repair of buildings are also included in this stage. The use of water for various purposes like sanitization, filtration and construction also contribute significantly to the carbon footprint (Kwok et al., 2016).

The location of the building notably affects the carbon emissions. The use of public transportation like metro and local rails helps in reducing the carbon emissions as compared to the use of taxis, cars and other vehicles. The inclination towards the use of renewable energy resources and net-zero energy building units is reducing the carbon emissions coming from the operational stage.

End use stage

The demolition of buildings contributes less to the carbon emissions compared to other stages. By moving towards the recycling process, the GHG emissions can be further reduced. The consumption of energy for the annihilation of buildings and the transportation of the demolished material to the landfill site put in majorly towards the GHG emissions (Junnila et al., 2006).

Electricity

Electricity generation is the main contributor to the world's carbon emission. With the development of the countries and their urbanization, electricity consumption is growing continuously. The carbon emissions coming from the electricity sector can be categorized into three broad classes. The foremost is the production based carbon emission that includes power generation, other is the supply based carbon emissions that refers to the electricity supplied in local regions and the third one is the consumption based carbon emissions that covers the electricity consumption in daily life (Kennedy et al., 2009).

The world's growing energy needs are met by fossil fuel consumption that mainly includes the utilization of petroleum products for electricity generation. The environmental pollution, energy consumption and the economic growth are all found to be interrelated as per latest research reports. The electricity is an incentive for any country's growth and its shortage may adversely affect the growth but the electricity conservation policies can be designed in such a manner that my not hinder with the growth. The literature shows that one third of the electricity is used by the residential sector and the exploitation of electrical appliances contributes maximum to the electricity consumption (Ramaswami et al., 2017). The development of new technologies to design sustainable electricity production, distribution methodologies and smart consumption behavior is mandatory to mitigate the consequences of carbon emissions from electricity consumption and production.

Household

The household carbon footprint varies with several socio-economic, demographic and cultural factors. The household expenditure is the major factor responsible for increasing carbon footprint. The research shows the direct relationship between the two. It has been noticed that as the household gets more affluent, the consumption of the household also shifts to more value added products or higher service based good and services. The wealthier household tends to spend more on luxury based items in comparison to necessities like food and shelter (Girod et al., 2010). Several features like the location and the size of the house, living style, eating habits and many more mingle together to decide the final outcome of the carbon footprints. The cultural differences, climate variation, technological deviations and consumer behavior are other factors affecting the CFs. The research shows that the high expenditure households contribute nearly seven times more than the low expenditure households. This shows that extreme

poverty is not at all responsible for ruthless climate change in our country. The cities occupy jut 2% of land but it contributes 70-80% towards carbon emission. The increasing urbanization is also affecting the climate change to the vast extent (Lebel et al., 2007).

The India's contribution towards global carbon emission is increasing to the vast extent and this owes to its rapid and irregular economic expansion further leading to unbalanced distribution of wealth and industry. Cast, religion and regional factors are further responsible for the same. The difference in the consumption patterns of food, transport and energy usage are important determinants of carbon footprints from households. There is a large divergence between the CFs of different districts with Gurgaon having the highest CF and Baudh having the lowest one (Gupta et al., 2018)). Regional diversity is also observed between the Eastern and Western areas with the East area having lower CF than the West region. Likewise, Coastal areas have higher CF than the inland regions and mega-districts have higher CF compared to hinterland areas. In districts having low poverty rates, CFs are more highly related to population densities but the districts with high poverty rates, such correlation is vague.

Moreover, the type of food intake also varies among the households as rice is the highly demanded food whereas milk is preferred by the wealthier households (Ivanova et al., 2016). The wealthier households also have preference for cooked foods, luxury items, ornaments and durable goods. Among the other food items, grain consumption is mainly preferred by low and medium expenditure households while the expenses on animal products, fruits, restaurants, alcohol and other beverages are limited to high expenditure groups (Beauer, 2023)

The contribution of electricity consumption, transport and goods towards the CFs is also noteworthy. However, the contribution of expenditure on other sources of energy, medical care and education is least among the household CFs.

The differences between the carbon footprint of various citizens of India can be resolved by assigning special individual responsibilities to design national and global climate change policy. Decisive actions are needed to reduce the scale and impact of climate change. One way is to focus on the changes in the consumption pattern.

Highway Construction Materials

The increasing urbanization requires more infrastructure development that adds to the increasing carbon emissions. Pavement designing, production of

materials and their transportation, construction practices and vehicular operations are the major GHG contributors. The construction stage involves 3 main steps: (i) Land clearance (ii) Pre paving operations (iii) Paving and post paving operations. Another factor is the actual traffic count that runs during the entire life of the pavement (Sreedhar et al., 2016). The vehicular damage factor, lane distribution, type of vehicles like truck or commercial vehicles decides the actual amount of carbon emissions during the pavement life. Different combinations of materials for concrete result in different amounts of carbon emissions.

Methodologies for the Estimation of Carbon Footprints

Electricity

There are various methods for calculating the environmental footprints of electricity production based on the problem. Basically there are two types of attribution methods based on grid infrastructure and based on geographical boundaries. The method based on grid infrastructure confines the production, transfer and consumption of electricity to the underlying grid but this method requires too much of computational work. On the other hand, geophysical boundaries does not depend on the actual flow electricity along the grid but the GHG emission national policies are often based on these boundaries (Siddik et al., 2020)

Household

There are two main approaches to calculate carbon emissions at district level. Foremost is the Areal carbon footprint and other is the Personal carbon footprint. Areal CF is limited to the total expenditure within a particular geographical area. This approach collectively includes the residential expenditure, tourist outflow, governmental spending and capital generation. However, Personal CF is entirely based on the residential expenditure that is more focused on the individual consumption behavior and the further impact on various expenditure categories. This approach does not include any carbon emissions based on government spending and capital generation (Heinonen et al., 2020)

Buildings

The estimation of carbon emissions from buildings is imperative to work on mitigation strategies. The carbon emission from buildings is based on various

factors but the basic framework is Life-Cycle Assessment (LCA) process. In this approach, the various products and attributes related to building like the extraction of raw materials, manufacturing of building materials, transportation, operation, disposal and recycling are assessed throughout their life cycle. The interest in the LCA approach to estimate CFs from buildings and related products is increasing these days in order to design such materials that are more environmental friendly. Basically there are three types of LCA approaches:

- Process Based Approach
- Economic Input-Output Analysis
- Hybrid Approach

Process Based Approach

This approach makes the use of inputs and outputs for each process. It is a highly accurate approach and thus followed for majority of analysis. However, this approach needs high amount of data from multiple resources thus making this methodology expensive and time consuming (Suh & Huppes, 2005).

Economic Input-Output Analysis

In this approach, the emissions are studied for large supply chains. The geographical boundaries are made for the selected area and the input-output database like energy consumption, emissions and capital goods are studied. Due to easy availability of data, this model is easy to handle and less time consuming as well. Moreover, this approach requires less effort, is more consistent, includes both direct and indirect emissions which make it a better model compared to process based approach (Minx et al., 2009)

Hybrid Methodology

As the name suggests, this method coalesce the properties of both the process based and economic input-output approaches. This approach provides detailed knowledge about the products using process based analysis as well as general information given by input-output analysis. Hybrid approach is further divided into tiered, input-output and integrated analysis (Suh et al., 2004)

Agriculture

Various approaches are designed to estimate carbon footprints from agriculture sector that considerate soil properties, crop variety and other

agricultural practices. Variety of models include characteristics of soil like soil acidity, water content, soil texture and temperature. These models study about the change in soil nature with the time. These are easy to apply models but they are less pertinent at global level because it considers only soil factors. The better model is dynamic crop-climate soil model that covers all the factors (Goglio et al., 2015). Emission factor methodology is also used to estimate carbon footprint of various crops like wheat, maize and sunflower but this method also has few limitations like it is region specific and is less focused on the combined effect of soil, climate and crop variety.

Methodologies to Reduce Carbon Footprints

All the people must come forward to combat this alarming dilemma of rising carbon emissions. There is a need to alter day to day consumption activities to tackle climate alterations. Abundant moderations can be made on individual bases to make the greener and low carbon lifestyle. To mitigate the carbon emissions from agriculture sector, various agricultural practices like crop diversification, summer fallowing, rotating the crops like rice with maize, application of biochar, organic farming, and usage of biofuels in place of fossil fuels (Pawlowski et al., 2017).

Crop diversification increases the productivity as well as lowers the carbon emissions. Nitrogen fertilizers are the main sources of GHG emissions. So, rotating the leguminous crops with non leguminous ones reduces the carbon emissions (Liu et al., 2016). Also, some techniques like Green seeker and some chemically modified urea fertilizers help in reducing carbon footprint of Nitrogen fertilizers (Nath et al., 2017).

For our day to day use, renewable energy resources must be prioritized, preference for electric vehicles, increase in government based environmental subsidies and active participation in global drive for adopting low carbon lifestyle. Consumer behavior is deciding factor for the sustainable consumption. Consumers can go for more sustainable goods or sharing or borrowing a product rather than purchasing it. Consumers can also go for repair and upgrading the product they own rather than going for new purchase and if the product has reached its end then it must be smartly disposed of (Schor & Fitzmaurice, 2015).

To reduce the carbon footprints coming from the buildings, the upcoming trend of green building movement must be followed. The green building movement is mainly based on reducing the carbon emissions from the design and making of building material, reduction of emissions from operational stage and emissions from other phases of building. These days buildings are being designed with low energy consumption which has been possible by the reduction in the emissions at operational stage (Kofoworola & Gheewala,

2008). Further, reuse of materials and proper design for the disassembly of the building also provides a very good method of reducing the carbon footprint arising from the end of building life. The carbon emissions from health care sector can be reduced by following more sustainable medical procedures and devices with low carbon emissions (MacNeill et al., 2017).

Conclusion

The carbon footprint study provides the overall insight about the role human activity is playing in accelerating the environmental degradation and worsening the climate change. The data clearly reveals that global carbon emissions are abundantly increasing thus creating an urgent need to look for effective mitigation strategies. Several challenges have been discussed in the paper that hinder the way towards low carbon life but through integrated efforts of the individuals, societies, industries and government policies we can achieve significant reductions in carbon emissions. These steps can ultimately lead to sustainable development that aims for the economic growth along with ensuring the well being of the future generations.

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CHAPTER-08

EXPLORING THE MULTIPLE WAYS CLIMATE CHANGE ENDANGERS AMPHIBIAN BIODIVERSITY

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Abstract

The escalating loss of biodiversity has resulted in the dramatic reduction of populations and rise in species extinctions, specifically targeting the amphibians. Although there are several reasons for the reduction of amphibian populations, climate change is a multifaceted threat at the individual, population and community levels. Climate change affects many aspects like range, survival, growth, reproduction, dispersal and susceptibility to disease. Habitat degradation, caused by vegetation, soil and water system alterations, distorts the food webs, predator-prey associations and competition interactions, eventually redrawing entire communities. The synergistic effects of climate change, combined with other stressors such as UV-B radiation, pollutants and emerging diseases form a deadly cocktail that affect amphibians. An understanding of these complex interactions is a key for developing effective conservation plans. To reduce the cascading impacts of climate change on amphibians, an integrated strategy is necessary, including

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research, habitat conservation and minimizing anthropogenic stressors to protect this ecologically important group.

Keywords: Emerging diseases, environmental stressors, global warming, habitat degradation, species interactions

Introduction

The worldwide biodiversity crisis is gaining prominence, with extinctions taking place at an unseen scale and amphibians are one of the most adversely affected groups (Lawler et al., 2009). Globally, there are more than 7,500 amphibian species, with about 450 species present in India. Amphibians in India are also under immense threat, with the extinction of species like the Golden frog and the Gharial (Gururaja et al., 2023). Amphibians are known to be "canary in the coal mine" as they are sensitive to certain environmental stressors, such as habitat loss, pollution, invasive species, emergent disease like Chytridiomycosis and climate change (Blaustein et al., 2001). These stressors, especially climate change, interact and create a lethal combination that impacts amphibians at individual, population and community levels (IPCC, 2007). This chapter discusses the ways in which climate change, such as increasing temperature, changed precipitation regimes and extreme climate events, affects amphibian populations. Climate change causes range shifts in species (Bickford et al., 2010), disruption in life cycles (Kiesecker, 2011), and breeding patterns (Blaustein et al., 2001). Moreover, changes in temperature synergistically increase the effects of stressors like pollution (Bancroft et al., 2008) and new diseases (Lips et al., 2006), generating a "deadly cocktail" that drives population declines. This chapter integrates recent studies to present a thorough overview of the multi-faceted impacts of climate change on amphibians, providing useful insights for the formulation of focused conservation measures to counteract these effects on amphibian diversity worldwide.

Amphibian vulnerability to the Looming Climate Crisis

Environmental scientists alerted the world in the 1970s to two large-scale human-triggered environmental changes: global warming and ozone depletion. Global warming was expected as a result of fossil fuel combustion, land use change and deforestation, while ozone layer damage was due to the discovery of chlorofluorocarbons (CFCs) and other industrial pollutants and resulting elevated concentrations of toxic ultraviolet-B (UV-B) radiation reaching Earth's surface (McMenamin et al., 2008). These issues have developed into a climate crisis since then, with reports from the

Intergovernmental Panel on Climate Change (IPCC, 2007) and the United Nations Environment Programme (Corn, 2005) detailing the rising global temperatures, melting of glaciers and ice sheets, sea level rise and intensified extreme weather occurrences. Shifts in precipitation regimes have resulted in flooding in certain regions and droughts in others (Corn, 2005), all of which affect ecosystems and biodiversity by changing species distribution, phenology and interactions (Blaustein et al., 2001). While the Montreal Protocol has succeeded in decreasing ozone-depleting substances, recovery of the ozone layer is slow and high UV-B radiation is likely to continue for decades (Bustamante et al., 2005). Exposure to enhanced UV-B is known to produce DNA damage, cellular dysfunction and reproductive abnormalities (Raxworthy et al., 2008). Combined impacts of ozone depletion and climate change are a major threat to biodiversity and species are already shifting their ranges, phenology and behavior (Parmesan, 2006). Species, which cannot adapt at a fast pace may suffer declines in populations, local extinctions or extinction (Molur et al., 2008).

Impacts of climate change on amphibians:

The impact of climate change on amphibians can be classified as either direct or indirect. Directly, climate change can affect amphibians through changes in temperature and precipitation patterns, which in turn influence their physiology, development and behaviour (Lawler et al., 2009). Indirectly, climate change can alter amphibian habitats and food resources, as well as species interactions. Changes in vegetation, hydrology and phenology due to climate change can impact the availability of breeding and foraging habitats, disrupt trophic dynamics and alter the synchronization between amphibian species and their prey or hosts (Bickford et al., 2010). Climate change has a tendency to intensify other forms of threats, such as epidemics of disease, invasions by other species and environmental contamination, thereby increasing the pressures on amphibian populations (Cohen et al., 2017).

Direct impact of climate change on amphibians

It includes demographic, behavioural and physiological impacts and indirect impact includes which are discussed below.

Demographic impact of climate change on amphibians

Climate change can alter wild amphibians' distribution, connectivity, abundance and persistence (Vasudevan et al., 2018).

(a) Shift in range of amphibians

Climate change is expected to strongly affect amphibians in India. Vasudevan et al. (2018) employed ecological niche modeling to illustrate how Western Ghats frogs could experience range contractions and shifts, with their extinction potentially threatened under future climate scenarios. Dheer et al. (2022) reported that Himalayan amphibians, particularly those with a relatively restricted range and specific habitat needs, are very sensitive to altered climatic conditions. At a global level, the 2022 IPBES report referenced climate change as one of the largest drivers of biodiversity loss (IPBES, 2022). For these reasons, amphibians are extremely vulnerable since they are highly sensitive to environmental changes and cannot disperse over large distances (Lawler et al., 2009). According to Raffel et al. (2015), about 39% of amphibian species were expected to become extinct by the end of the century. Tropical regions, including Central America and the Amazon basin, are particularly at risk. Urgent conservation measures recommended by the study included habitat protection, assisted migration, and ex-situ efforts (Bickford et al., 2010). To demonstrate how severe impacts might occur in Central America, with high species turnover due to hotter and drier conditions affecting species with restricted ranges, Lawler et al. (2009) used bioclimatic models.

Physiological impact of climate change on amphibians

(a) On breeding phenology

Climate change affects amphibian reproduction most prominently through changes in reproductive phenology. For example, a number of species across the globe start breeding earlier as temperatures increase and precipitation becomes more erratic. Changes in breeding phenology are reflected with the impacts of climate change in India. According to Seshadri et al. (2019), warmer temperatures as well as the delay in monsoon precipitation have altered the seasonal breedings of the Indian Golden Frog *Indirana semipalmata*. Similarly, the same kind of alterations in rainfall patterns at the Western Ghats have also affected the Critically Endangered Kodagu Swimming Frog *Hylarana montanus*, as reported by Gururaja et al. (2023).

Around the globe, many amphibians are breeding earlier in response to climate change. Corn, 2005 documented earlier breeding in British anurans and analogous patterns in Japan (Blaustein et al., 2001) and *Triturus* newts (Lawler et al., 2009). Responses vary; in New York State, while some anurans bred earlier, others did not (Rohr et al., 2008). Such shifts could alter

amphibian assemblages, as species that previously did not overlap in breeding habitats might now do so, creating new biotic environments for larvae. Temperature and precipitation are the two environmental stimuli, which are very strong possible factors of reproduction. Blaustein et al. (2001) associated temperature with breeding date in several species. In Romania, February temperature is the most important predictor variable for timing breeding in Agile Frog (*Rana dalmatina*) (Gervasi et al., 2013). Precipitation events also trigger breeding in diurnal toad (*Melanophryniscus rubriventris*) (Vasudevan et al., 2018). Climate change may also impact other aspects of reproduction. Warming can reduce dissolved oxygen (DO) in aquatic habitats, which impacts the development of embryos and larvae. The poor availability of oxygen can slow the development in mole salamanders, *Ambystoma* spp. (Bancroft et al., 2008) or induce the hatching of frogs, *Rana* spp. earlier but at a smaller size (Gervasi et al., 2013). Elevated temperatures could also disrupt sex ratios by making females scarce, thus reducing reproductive success (Bickford et al., 2010). Overall, climate change impacts the reproduction of amphibians in complex ways, whether interacting with timing, development, behavior, or sex determination. New findings, for instance, include those by Muñoz et al. (2023), emphasizing that this is what should continue studying these impacts and directly inform conservation action from them.

(b) On development of amphibians

Changes in temperature due to climatic alterations would probably impact amphibian development and survival significantly, changing population dynamics. This is seen both in India and worldwide. For instance, in India, Kusano and Inove (2008) demonstrated that higher temperatures meant increased embryo development for the Indian Bullfrog, *Hoplobatrachus tigerinus*, at increased mortality thus a trade-off. Gaitonde and Gaitonde (2021) have noted that breeding phenology as well as the larval development of the Indian Skittering Frog (*Euphlyctis cyanophlyctis*) is going to be affected by increased temperatures in an urban setting.

Temperature influences on development in amphibians are widely understood globally. In general, developmental rates are increased until a species-specific threshold is encountered (Rohr et al., 2008). For example, Volpe showed that Western Toad (*Bufo valliceps*) embryos develop satisfactorily between 20-33°C; but survival decreases outside this range. If temperatures are elevated outside of the tolerance band, survival can decline drastically and thus could potentially threaten populations (Bickford et al., 2010). Temperature during embryonic development could also impact later life stages, as well as population level processes (Kiesecker, 2011). Survival and growth of larvae also depend on temperature. For instance, survival in Pacific Treefrog

tadpole, *Pseudacris regilla*, is dependent on its density with rearing, whereby increased temperatures correlate with higher survival at lower densities but a lesser survival at higher densities (Bancroft et al., 2008). In most cases, there is an increase in temperature that limits the duration to metamorphosis and leads to smaller size at metamorphosis with this trade-off between developmental rate and growth (Gervasi et al., 2013). The effect can be influenced by other factors, including food availability (Seshadri et al., 2020) and hydroperiod (Gaitonde & Gaitonde, 2021). Shorter larval periods may improve survival opportunities in transient habitats but produce smaller metamorphs that are characterized by poor post-metamorphic performance and immune functions (Rohr & Raffel, 2010). Even temperatures above 32°C can affect successful metamorphosis rates (Vasudevan et al., 2018). Recent research has also documented how climate change is potentially altering this coordination between amphibian development and environmental cues to produce phenological mismatches. Parra et al. (2023) concludes that warmer temperatures across the Mediterranean create advanced breeding and larval development times, which could deleteriously mismatch with food availability and increase the risk of desiccation. General impacts on ontogenetic and survival stages of amphibians and their population dynamics are likely to pose a compelling reason for continued study and conservation management to mitigate climate change influences on these species.

Behavioural impact of climate change on amphibians

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Indirect impact of climate change on amphibians

Climate change and global warming are expected to indirectly influence amphibian populations via changed habitats, food webs, species interactions, and disease patterns. In India, Vasudevan et al. (2018) reported that climate change may result in habitat loss, changes in species interactions, and endanger endemic species in the Western Ghats. Seshadri et al. (2019) emphasized that increasing temperatures and changed rainfall could desiccate Indian Golden Frog (*Indirana semipalmata*) ephemeral breeding pools, putting its survival at risk. Global warming can exacerbate habitat degradation through a change in temperature and precipitation, as well as interfere with breeding sites, food supplies, and refugia, affecting the survival and reproduction of amphibians. Increasing temperature facilitates the transmission of diseases like chytrid fungus (*Batrachochytrium dendrobatidis*), which prefers specific climatic conditions and could pose threats to amphibians globally (Blaustein et al., 2001). These conditions usually involve interactions, producing cascading impacts. For instance, habitat destruction elevates amphibian stress, compromising immune function, and rendering them vulnerable to disease (Rohr & Raffel, 2010).

Current research highlights an integrated conservation approach addressing the intricate interactions of climate change, habitat loss, disease, and invasive species (Böhm et al., 2023).

(a) Destruction or fragmentation of natural habitat

All frogs, despite their type of eggs as being non-aquatic, still require some fresh water for successful spawning. Thus, making them highly vulnerable to climatic changes in the aspects of temperature and precipitation that affect both aquatic and terrestrial habitats that are crucial to the survival of these frogs. Overall, the climate change research in India seems to be orientated towards breeding habitats of amphibians, which have the maximum potential for impacts. Vasudevan et al. (2018) found that elevated temperatures and decreased rainfall may cause dewatering of the ephemeral pools and streams of the Western Ghats, resulting in reproductive failures and population declines. Similarly, Seshadri et al. (2019) reported that a shift in precipitation and enhanced rates of evapotranspiration can diminish the hydroperiod of ephemeral pools because these had poor reproductive efficacy and were susceptible to high predation for the Indian Golden Frog (*Indirana semipalmata*). Amphibians breeding in seasonal aquatic sites, including vernal pools and headwater streams, are extremely sensitive to alteration of the climate across the globe. In regions where local rainfall increased, but nevertheless droughts and dry-out of significant aquatic resources, losses from potential evapotranspiration might be higher than gains in areas where local rainfall increased. Hydroperiods being shortened and a stream flow regime altered, certainly result in more frequent reproductive failures (Gururaja et al., 2023). Sea-level rise and increased storminess bring new challenges to coastal freshwater wetland species: habitat loss, saltwater invasion, and fish predators. Full terrestrial species such as Plethodontid salamanders that tolerate moist conditions but may easily desiccate are also vulnerable to terrestrial habitats, such as soil moisture and vegetation. The changes in the plant communities of the wetlands affect the reproduction and recruitment of amphibians. Wetland hydroperiod favors grass and woody species because it is relatively low, while long hydroperiod allows an aquatic species to thrive there (Lips et al., 2006). Changes in vegetation also confer changes to the accompanying microclimatic factors that affect the reproductive success. In fire-dependent systems, climate change-induced changes in fire regimes may lead to invasive species and changed wetland conditions that compromise amphibian metamorphosis (Raxworthy et al., 2008). Modern research is conducted on holistic approaches to conservation by addressing all the impacts brought about by climate change on the amphibians' habitats. Böhm et al. (2023) suggest that in implementing

conservation plans for amphibians, one should consider climate change, land-use change, and invasive species.

(b) Availability of food resources

Climatic changes may exert significant influences on the dynamics of a food web and resource availability for tadpoles and larval salamanders—the two most critical functional roles, as both being ecosystem engineers and consumers in freshwater ecosystems. In India, research has been successful in proving that climate change influences aquatic habitats and therefore acts upon food resources for larval amphibians. Altered precipitation and increasing water temperatures are likely to affect the availability of algae, detritus, and invertebrate prey of the Critically Endangered Kodagu Dhole, *Nasikabatrachus sahyadrensis*, and these are likely to affect tadpole growth and survival (Raxworthy et al., 2008). Seshadri et al. (2022) indicated that rising water temperatures might precipitate cyanobacteria blooms, thereby significantly impacting food webs, water quality, tadpole survival, and developmental capacity. Tadpoles are ecosystem engineers, involving resources and affecting other consumers, in various freshwater habitats across the globe. Their diets are diverse and could be herbivorous or carnivorous. Increased nutrient cycling and primary production due to increasing temperature may be beneficial, but increased water pollution and algal blooms associated with higher temperatures will negatively affect food availability and tadpole growth (Blaustein et al., 2001). Larval salamanders are gape-limited carnivores, relying on aquatic invertebrates (Rohr et al., 2008). Climate change may impact wetland hydrology, thereby influencing consequences for invertebrate populations and salamander densities and biomass. A 1°C increase in water temperature in the northeastern United States may decrease spring macroinvertebrate abundance by 21% (Bickford et al., 2010). Changes in hydrologic regime affect aquatic insect and zooplankton biomass; increases in hydroperiod might enhance prey availability for salamanders (Molur et al., 2008). In terrestrial amphibians, heavy precipitation can increase humidity at the forest floor and enhance the availability of prey, thus enhancing foraging chances and reproductive success (Lawler et al., 2009). Gururaja et al. (2023) revealed a connection between the previous year's rainfall and the clutch size of the western slimy salamander (Seshadri et al., 2020). Food supply impacts individual fitness in various species of salamanders (Bancroft et al., 2008). Climate modeling, joined with community ecology and population dynamics, has recently been highlighted as a requirement for understanding and mitigating the effects of climate change on the habitat of amphibians (Böhm et al., 2023).

(c) On structure and dynamics of amphibian communities

Climate change has significantly impacted the amphibian communities in their altered distribution patterns, breeding phenology, facilitation of invasive species, and modifications in interactions with keystone species. Climate change impacts on amphibian communities in the Indian scenario, especially in biodiversity hotspots such as the Western Ghats, are particularly noteworthy. Vasudevan et al. (2021) reported that climate change can trigger range contractions and shifts for most frog species, thus altering competitive interactions and community structure. Gururaja et al. (2023) reported differential changes in breeding timing among species that could disrupt temporal overlaps between competitors, predators and prey, thereby affecting community dynamics and trophic interactions.

Climate shapes species distributions and competitive interactions in contact zones everywhere on Earth (Vasudevan et al., 2018). Phenological shifts in breeding due to climate will alter the temporal covariation among aquatic breeders, an influence on the community structure. Climate change is projected to change the probability of persistence and spread of non-native species, but will likely expand invasive ranges by others, including the Cuban treefrog (*Osteopilus septentrionalis*), American bullfrog (*Lithobates catesbeianus*), and cane toad (*Rhinella marina*), which will likely worsen declines in native amphibians. Climatic changes affecting keystone species, such as mole salamander (*Ambystoma talpoideum*) and eastern newt (*Notophthalmus viridescens*), could have significant cascading effects on amphibian communities (Rossin- Smith 2017). For example, an amphibian keystone species, such as the eastern newt, can reduce the effects of invasive Cuban treefrog tadpole competition on native tadpoles (Dheer et al., 2002). Climate change, by shortening breeding site hydroperiods, could therefore undermine these keystone species, changing the community structure in wetlands. Recent studies emphasize that management programs need to take holistic approaches, incorporating both climate change and invasive species impacts on the amphibian fauna biodiversity (Lips et al., 2006).

(d) Disease emergence

The prevalence and intensity of some pathogens will be increased and others may be reduced due to the changed environmental conditions caused by climate change (Raj et al., 2021). It is hard to predict the overall disease burden on amphibians of India because of the complex interaction between the climatic factors, dynamics between hosts and pathogens, and the transmission of diseases (Rohr et al., 2006). Climate change can uproot host-pathogen balances and may cause disease outbreaks or affect changing the

virulence of pathogens (Corn, 2005). Amphibians, in general, are very rich in diversity in India, and the impacts of climate change can severely affect both the conservation and health of ecosystems (Parmesan 2006). Change in temperature and precipitation patterns and habitat fragmentation may favor some pathogens over others while compromising the immune competency of amphibians. Climate-driven epidemics affecting amphibians and their ecosystems need to be monitored regarding these disease dynamics. Climate change impacts on diseases affecting amphibians vary widely across the globe. In most host-pathogen systems, epidemics are likely to be increased, although severity may be lower in some (Vasudevan et al., 2018). Climate change leads to the disruption of balances between hosts and pathogens and favors increasing the latter's proliferation (Vasudevan et al., 2018). The changes in climate affect host and pathogen distributions, pathogen virulence, and host susceptibility. An increase in temperature may allow the pathogen range to extend into new areas, thus exposing naive amphibian populations to the diseases. Changes in precipitation and habitat degradation may stress amphibians, thereby weakening their immune defenses (Vasudevan et al., 2018). Climatic change can also lead to the appearance of new diseases or the resurgence of controlled pathogens (Blaustein et al., 2001). Solutions to these global impacts will be through interdisciplinary research, international coordination, and coordinated efforts in conserving species (Böhm et al., 2023). It will all depend on ongoing monitoring, advancements in disease ecology, and predictive modeling in the protection of amphibian biodiversity in the presence of climate change (Vasudevan et al., 2018).

(e) Immunity

The immune function and the susceptibility to diseases in amphibians have drastically changed in the rich habitat of India due to climate change. The immunity of ectothermic amphibians changes with low and high temperatures; low temperatures depress some crucial components of their immunity, but some innate responses remain unchanged at stable values (Blaustein et al., 2001). Climate change-related alterations in hydroperiods cause desiccation stress, which increases pathogen susceptibility and weakens the immune responses of larvae (Biju & Bossuyt, 2003). The energetic costs for frequent regulation of the immune system from temperature fluctuations are quite high, and lags in responses of the immune system provide windows of vulnerability to disease outbreaks (Böhm et al., 2023). This understanding is much needed for conservation efforts in India's wonderfully diverse amphibian population, particularly in places like the Western Ghats (Seshadri et al., 2022). Amphibian immunity to climate change is an urgent concern worldwide (Kiesecker, 2011). Low temperatures inhibit many immune components, although some innate responses are stable or increased even in

some species (Bancroft et al., 2008). Shifts in hydroperiod as induced by warmer temperatures impose desiccation stress, which is detrimental to many immune functions and increases disease susceptibility (Blaustein et al., 2010). The energy costs of maintaining a continuous immune modulation under fluctuating temperatures and the latent time of immune responses contribute to increased disease susceptibility (Gervasi et al., 2013). It would then be possible to understand the interplay between temperature-dependent immunological changes, physiological demands, and environmental stressors as an important basis for designing effective conservation strategies both globally and locally (Bickford et al., 2010).

(f) UV-B radiations

The increase in UV-B due to ozone depletion threatens all amphibians worldwide (Blaustein et al., 2001). Although temperature increase could advance the breeding season, thus alleviating the adverse impacts of increased UV-B, the interaction of temperature and UV-B has synergistic effects on the survival of amphibians (Bancroft et al., 2008). The interaction of low temperature and UV-B radiation significantly reduces larval survival, probably through reducing DNA repair enzyme activity and changing behavior (Altizer et al., 2013). Amphibians living in cold, high UV-B environments are specifically more vulnerable (Bickford et al., 2010). With the increase in temperature and associated changes in global warming, the overall consequences for amphibians caused by UV-B are highly unpredictable (Blaustein et al., 2010). As India happens to be a biodiversity hotspot in the Western Ghats, the case with amphibians is the same: they are victims (Gururaja et al., 2023). Consequently, populations at higher altitudes are more sensitive to UV-B compared to low-altitude counterparts (Gervasi et al., 2013). Changes in climate would therefore shift the breeding patterns but definitely won't suffice to overcome UV-B effects on larvae (Seshadri et al., 2022). Important population-monitoring activities toward protection measures and further devising suitable conservation strategies against climate change and UV-B radiation are necessary for the conservation of amphibians in India (Abraham et al., 2013).

Conclusion

This chapter outlines the intricate impacts of climate change on amphibians at ecological scales and untangle key mechanisms interacting with direct and indirect impacts with other stressors in the environment to force collapse in numerous amphibians. By doing so, we endorse a multi-disciplinary framework combining climatic modelling and experimental research and the use of molecular tools to forecast these impacts, pinpoint vulnerable species,

and guide conservation measures. This chapter brings out the necessity that the process has to be collaborative in the aspect of minds coming together to strategize and explore the impact of climatic changes on amphibians and formulate stronger biodiversity-conserving methodologies to conserve the amphibians.

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CHAPTER- 09

GLOBAL APPROACHES TO BIODIVERSITY AND ECOSYSTEM MANAGEMENT

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Abstract

Biodiversity is the variety and variability of Life on Earth, which includes variety of genes, populations, species, communities, ecosystems, and ecological processes. From genes to micro-organisms to top predators and even whole ecosystems, humanity depend on biodiversity for everything from clean air and water to medicines and secure food supplies. In spite of the growing awareness of the importance of ecosystems and biodiversity to human welfare, loss of biodiversity and degradation of ecosystems still continue on a large scale. There is increasing recognition that a deteriorating global environment poses not only growth and development. Strategic approaches that integrate biodiversity conservation and livelihood goals are necessity of the time. Creating or highlighting explicit interdependencies emanating from unsustainable natural resource exploitation and contribute to human wellbeing by improving human quality of life in areas of conservation concern.

Keywords: Biodiversity, Environmental challenges, Climate change, Sustainable livelihood.

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Introduction

Since 1753, when Carolos Linnaeus proposed the binomial system of nomenclature, 1.5–1.6 million species of diversified organisms have been recognized and named in a formal, taxonomic sense. Approximately 750,000 of these are insects, and 250,000 are plants. The remainder consists of other invertebrates, vertebrates, fungi, algae, and microorganisms. At least twice the total number of known species remains undescribed: these are primarily insects and other arthropods, especially those inhabiting tropical forests. Our knowledge of species numbers is imprecise because inconspicuous species, such as spiders, nematodes, and fungi living in the soil, have not received a proper taxonomic attention (Barthlott & Winiger, 2001).

Biodiversity is an umbrella term to refer to all the living organisms present in an area. The term "biodiversity" was coined in late 1988 by E. O. Wilson. The term includes all life forms present on the earth starting from plants, animals, microorganisms, bacteria, virus, aquatic organisms and even coral reefs. Biodiversity denotes the species richness as well as species evenness. Genetic, organism and ecological diversity are all forms of biodiversity at different scale with different components. Biodiversity is considered as a repository of resources. It is used to manufacture the food, medicine, industrial products, etc. Till date a huge number of diversity is known but currently biodiversity is constantly depleting with an increased demand of rapid population growth (Berkes, 2013). Human development and encroachment to the natural and wild habitat have led to the extinction of biodiversity due to the exhaustive agriculture & clearing of forests, mining for energy demands, transportation development and unregulated recreation. This loss has negative consequences on the delivery of ecosystem services and further on human wellbeing. Thus, protection of these species rich habitats should be the primary response (Mayr, 1942).

India's biological profile and status

India has a rich and varied heritage of biodiversity, encompassing a wide spectrum of habitats, from tropical rainforests to alpine vegetation and from semi-arid vegetation to coastal wetlands. India figured with two hotspots -the Western Ghats and the eastern Himalayas -out of 25 biodiversity hotspots identified by Myers (1988). In addition, India has 26 recognized endemic centres that are home to nearly one third of all the

flowering plants identified and described to date. Of the 1.7 million of the world's described biota, India contributes 7.3% of the global fauna (Binder & Polasky, 2013). Among flowering plants, India accounts for 7% of the 250,000 flowering plants so far described in the world. India is one of the 12 centers of origin of cultivated plants. There are 167 cultivated species and 273 wild relatives of crop plants. The endemism of Indian biodiversity is high. About 33% of the country's recorded flora (49,219 plant species) are endemic to the country and are concentrated mainly in north-east India, the Western Ghats, north-west Himalayas and the Andaman and Nicobar islands. In animals, the endemism among mammals and birds is relatively low (6 to 9%). However, the amphibians and reptiles are, respectively, nearly 62 and 50% endemic to India, and the majority of them are found in the Western Ghats.

Composition and types of biodiversity

There are three hierarchical levels of biodiversity in which it can be studied: Genetic diversity, Species diversity and Ecosystem or Community diversity.

Genetic diversity

The genetic information of all the living species is contained in their genetic material either in the form of DNA or RNA. This genetic variability contained in the genetic material facilitates adaptations in an organism and constitutes the genetic diversity of a species. The more the genetic variability, the more a species is likely to adapt and survive natural selection and other environmental pressures. Lesser the genetic variability, more are the chances of a species to be vulnerable to threats like fungal, parasitic and insect infestations and diseases.

Species Diversity

Many researchers have tried to explain this basic term of biology using different concepts. Over 20 different concepts are available that try to define the term, such as morphological species concept, ecological species concept, phylogenetic species concept etc. However, currently the most accepted concept is the biological species concept (Mayr, 1942). According to the biological species concept ‘‘groups of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups.

Ecosystem Diversity

The number of ecosystems present in a region constitutes its ecosystem diversity. Earth harbours a wide variety of ecosystems which can be

divided into terrestrial and aquatic. Aquatic ecosystems can be further be categorized into marine, freshwater and wetlands. Various types of terrestrial ecosystems are forest, grassland, desert, wetland, and tundra. Larger ecological systems are composed of biomes, which are fundamental units categorized on the base of vegetation and climatic parameters. Ecosystems like grasslands, rainforests, deserts and other ecosystems including aquatic ecosystems can be found a region, and make it ecosystem diverse. The more ecosystems diverse a region is, the more species diversity can be expected to be found there.

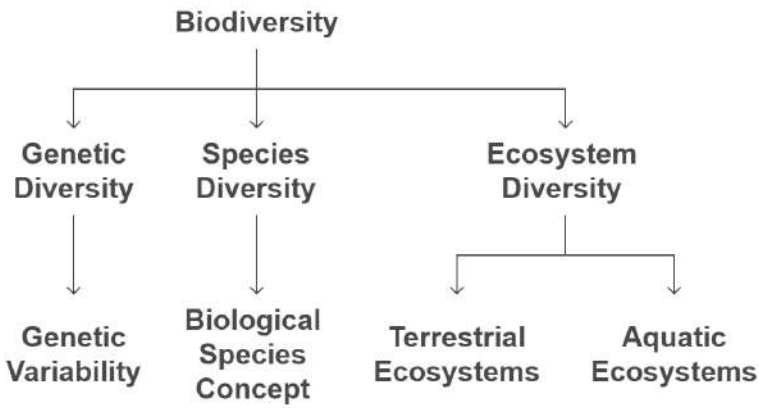


Figure 1. Biodiversity Hierarchy and Components

Biomes

Biomes are large geographical area categorized mainly on the base of vegetation and climatic conditions. The various biomes harbor different kinds of diversity. The major terrestrial biomes are as follows:

- ***Tropical rainforests****:* These forests are located on or near the equator, where the atmosphere remains humid with small or no dry season. They receive high rainfall and generally have acidic, nutrient poor soil. The decomposition rate is rapid; the nutrients released are also swiftly taken up by vegetation. Vegetation stratification is common and the canopy can be so dense that almost no direct sunlight reaches the ground. The biodiversity and productivity of these areas are very high. South America, Central America, Africa, South East Asia are the major parts of the world that harbour this kind of vegetation.
- ***Tropical seasonal forests***: These comprise of monsoon forests and many other forest communities with semi evergreen or deciduous leaf habit. In comparison to Tropical rainforests have a pronounced dry phase during

which the most of the trees partially or wholly shed their leaves. These forests are majorly found in India, South America, Central America South East Asia, Africa, Northern Australia and West Indies. These areas receive a large amount of rain although most this precipitation occurs in short periods.

- ***Tropical thorn lands and broadleaf woodlands***: These occur in tropics as well. Broadleaf woodlands occur towards drier climatic conditions. Cerrado of Brazil is a representative forest of the tropical broadleaf woodland where the canopy varies from closed to open, with or without scattered trees. Leaves on trees and scrub are large in size, branches are markedly twisted and the barks are thick and fire resistant. Cerrado occurs in the transition zone of Tropical seasonal and tropical thornwoods.
- ***Tropical Savannas and grasslands****:* Savannas are tropical grasslands with scattered shrubs or trees. The most dominant vegetation is of grasses like *Panicum*, *Andropogon*, *Pennisetum* and *Imperata*. Trees (mostly *Acacia* spp.) are scattered sparsely in the landscape. Savannas are most dominantly found in Africa, which has given rise to the most prolific diversity of grazers and browsers. Apart from Africa, tropical grasslands are found in Australia, South America and Southern Asia. Species richness is far lower in savannas as 14 compared to tropical rainforests. Loamy sand and summer rains less than 50 cm favors the sustenance of savanna. Frequent fires are common feature of tropical grasslands.

Table 1: Various names of grassland in different parts of the world

Country	**Name**
Australia	Down
Canada	Prairies
Mexico	Pampas
South Africa	Veldt
Brazil	Campos
Asia	Steppes

Source: Biodiversity Conservation and Management by School of Interdisciplinary and Trans-disciplinary Studies, IGNOU, New Delhi by S. Pant, 2022, p. 48. Copyright by Indira Gandhi National Open University, 2022

- ***Temperate rainforests***: These are forests found at higher latitudes than the tropics, with winter rainfall and develop in colder climatic conditions. Species richness is low as compared to tropical rainforests. *Sequoia, Pinus, Abies, Larix* and *Calocedrus* are some of the tree species found here. Trees easily acquire longevity of 500 years. A belt of mixed coniferous rainforests along the pacific coast of North America is a typical example.
- ***Temperate Forests:*** Temperate forests are divided into temperate evergreen forests and temperate deciduous forests. Temperate evergreen forest has trees with relatively small and broad leaves are found in the less humid, maritime climates in California, the Mediterranean region and southern Australia, whereas needle shaped evergreen forests (Conifers) are found in large areas of continental climates. The mixed forests of Sierra Nevada with Pine, Fir, Incense Cedar, and Sierra Redwood are also representative of temperate evergreen forests. In India, high altitude areas in Himalaya have abundant temperate evergreen forests. Temperate deciduous forests are mostly confined to northern hemisphere. The temperature may vary from -30° C to 38° C, without clear cut wet and dry seasons. Annual precipitation is between 600-2000 mm with moderately humid continental temperate climate with a prominent winter (Although not prolonged). Tree height is usually around 35 meters. Canopy is relatively open as compared to temperate coniferous forests. Growth period is 4 to 6 months which starts with snow melt in March-April and ends in autumn. Acorns and beech nuts are common. Bears, gray fox, gray squirrels are some of the animals found in these forests.
- ***Temperate grassland:*** These occur in areas receiving intermediate rainfall between deserts and forests. Long cold winters and hot summers is characteristic of these areas. The prairies of North America and steppes of Eurasia are the typical examples of this biome. They are also found in Africa *(Velds*) and Argentina (*Pampas)*. Mammals of these regions are either large running types like, Zebra, Bisons, Wild Horse, and Pronghorns or small burrowing type such as Prairie dogs and Ground squirrel. Big Bluestem (*Andropogon gerardii*), Wheat grass (*Agropyron smithii*) and Buffalo grass (*Buchloedactyloides*) are some of the grasses found in this biome.
- ***Desert:*** Deserts are mainly located in the subtropics, and receive very less annual precipitation. The amount of precipitation received can be used to classify deserts into different categories like hyper arid, arid and semi-arid. These areas can get extremely hot, especially during summers. Biodiversity is poor and vegetation is sparse with distinctive

low shrubs and xerophytic adaptations. Soil type is mostly sandy with or without salt crust. Sahara, Arabian Peninsula, west coast of South America, parts of Australia are typical examples of desert. Thar in the western region of India is the only desert in India.

- ***Taiga (Boreal forest):*** Extensive cover of coniferous trees is found in these areas. Trees like evergreen spruce, firs and pines dominate the landscape. These are found in areas unfavorable for the growth of broadleaf deciduous or 15 evergreen temperate forests. Summers are too short and winters, too long here. Species richness is generally low. Shrubs and under canopy trees are scarce. However, mosses and lichens may cover the entire ground surface. Taiga covers Eurasia to the northern parts of North America.
- ***Tundra:*** Tundra does not have climatic conditions that favors tree growth. The vegetation is mainly of lichens, mosses, grasses and dwarf shrubs that grow mostly during the summers when the permafrost thaws. Plants generally do not exceed the height of 10 cm because of low temperature, low sunlight, permafrost, strong wings, and low evaporation rate. Reindeer, Muskox, Caribou, Polar bears and Lemmings are prominent mammals.

Biological Diversity at National Level (Indian Biodiversity)

Every country is characterized by its own biodiversity depending mainly on its climate. India has a rich biological diversity of flora and fauna. Overall six percent of the global species are found in India. It is estimated that India ranks 10th among the plant rich countries of the world, 11th in terms of number of endemic species of higher vertebrates and 6th among the centers of diversity and origin of agricultural crops. The total number of living species identified in our country is 150,000. Out of a total of 25 biodiversity hot-spots in the world, India possesses two, one in the north-east region and one in the Western Ghats. Indian is also one of the 12 mega-biodiversity countries in the world.

Regional or Local Biodiversity

Biodiversity at regional level is better understood by categorizing species richness into four types, based upon their spatial distribution as discussed below

i. Point richness refers to the number of species that can be found at a single point in a given space.

ii. Alpha (a-) richness refers to the number of species found in a small homogeneous area

iii. Beta (b-) richness refers to the rate of change in species composition across different habitats.

iv. Gamma (g-) richness refers to the rate of change across large landscape gradients. a-richness is strongly correlated with physical environmental variables. For example, there are 100 species of tunicates in arctic waters, 400 species in temperate waters and 600 in tropical seas. Thus, temperature seems to be the most important factor affecting a-richness of tunicates.

India as a Mega-Diversity Nation

India is one of the 12 mega diversity countries in the world. The Ministry of Environment and Forests, Govt. of India (2000) records 47,000 species of plants and 81,000 species of animals which is about 7% and 6.5% respectively of global flora and fauna.

Values of biodiversity

The concept 'value' is most frequently used in a financial sense and it is confusing to account for non-monetary 'values' like the aesthetic worth of a landscape or the historical or even emotional importance of a location. The value of biodiversity and the products and services it offers are indicators of how ready a society is to make compromises in order to protect these natural resources. Nature and its component biodiversity have instrumental value only and should be valued like 28 any other commodities as per economists' viewpoints, while as per ecologists' viewpoints, the elements of nature have 'inherent' or 'intrinsic' value, and are therefore deserving of preservation and protection for their own sake. Biodiversity delivers tangible benefits that are of monetary value, such as crops and many other non-monetary values, such as pure air perceived by the beneficiaries. Moreover, biodiversity has often served both non-consumptive use like recreation and consumptive use like food and also the indirect use like pollination. Biodiversity directly contributes to human well-being in terms of the provision of foods, fuels, and fibres, and indirectly in terms of the provision of ecosystem services (ESs) (Binder and Polasky, 2013). Different types of benefits or values gathered from the biodiversity with examples are as follows:

1. Instrumental or utilitarian values

Instrumental or utilitarian values include both direct and indirect uses of biodiversity that address the economic benefits accessed by human beings for their own sake from nature. Sometimes, these values are related to monetary valuation and non-monetary benefits associated with many other ecosystem services (Hiron et al., 2018).

2. Intrinsic or Inherent Values

The intrinsic value of biodiversity can be defined as the values of each living being within itself as it exists and it has a variety of philosophical, religious, cultural, and ethical origins. It can be understood that every species being the entity of earth is valuable although it is not useful. Intrinsic values are indigenous in origin at any particular habitat and time and it is the result of a continuous evolutionary process (Alho, 2008). The global indigenous tribes have recognized the value of biodiversity and have given it an important place in their myth, culture, and traditions (Gray, 1999). The recognition of traditionally practiced integral human-environment relationships and the inherent connections between biological and cultural diversity is now being reclaimed by local peoples around the world (Golliher, 1999).

3. Ethical Values

Biodiversity has ethical values as every organism has the right to live, it teaches us the lesson to have compassion and care for other organisms. Ethical values depend on the understanding of humanity and come from ethics and the moral principles to judge right and wrong. Our ethical understanding of biodiversity is still in the early stages and it needs to be advanced (Bosworth et al., 2011).

4. Option Values

Biodiversity is a universal good. The future possibility to use biodiversity for the benefit of humankind is called option values. For instance, different species of plants, animals, and microorganisms might contain valuable compounds which may have the potential to cure dangerous diseases like cancer.

5. Recreation and Aesthetic Values

Aesthetics are generally defined as the enjoyment and pleasure felt through the observation of environmental scenery, characteristics of the observed object, beauty, and rarity. The aesthetic value of biodiversity means the pleasure and emotion that brings a positive response through visualization and observing the beauty of nature. It activates positive energy in our lives through music, literature, photography, tourism, paintings, emotions, and feeling. It also brings a positive social motivation for the conservation of nature and biodiversity by man through laws and policies, protected area networks, sacred grooves, and tribal efforts. The increasing use of the natural area for outdoor recreation will ensure its ecological integrity in the future. Natural area preservation and restoration contribute to aesthetic appeal and passive recreational usage.

6. Religious Values

Biodiversity is a part of the religious and cultural sentiments of the people around the world, especially the tribes. Many tribal communities worship nature, particular plants and animals as per the religious taboo and preserve it in a relict form known as sacred groves. Local communities safeguard it because of their adherence to their religious principles and long-standing customs (Khumbongmayum et al., 2004). Religion can provide emotionally compelling beliefs that can be used to implement adaptive solutions for resource management and biodiversity usage (Berkes, 2013). For instance, the use of flowers, bael Patta (leaves of *Aegle marmelos*), and tulsi (*Omimum sanctum*) in puja and Yagya in Hindu religious rituals provide the basis for their conservation. Conservation ethics and behavior in association with religion strengthen biodiversity conservation and prevents resource depletion ensuring a symbiotic relationship with sustainable development.

Threats to biodiversity

Extinction or elimination of a species is a natural process of evolution. In the geologic period the earth has experienced mass extinctions. During evolution, species have died out and have been replaced by others. However, the rate of loss of species in geologic past has been a slow process, keeping in view the vast span of time going back to 444 million

years. The process of extinction has become particularly fast in the recent years of human civilization. In this century, the human impact has been so severe that thousands of species and varieties are becoming extinct annually. One of the estimates by the noted ecologist, E.O. Wilson puts the figure of extinction at 10,000 species per year or 27 per day! This startling figure raises an alarm regarding the serious threat to biodiversity. Over the last 150 years the rate of extinction has escalated more dramatically. If the present trend continues we would lose 1/3rd to 2/3rd of our current biodiversity by the middle of twenty first century.

Let us consider some of the major causes and issues related to threats to biodiversity:

1. Loss of habitat

Destruction and loss of natural habitat is the single largest cause of biodiversity loss. Billions of hectares of forests and grasslands have been cleared over the past 10,000 years for conversion into agriculture lands, pastures, settlement areas or development projects. These natural forests and grasslands were the natural homes of thousands of species which perished due to loss of their natural habitat. Severe damage has been caused to wetlands thinking them to be useless ecosystems. The wetlands are destroyed due to draining, filling and pollution thereby causing huge biodiversity loss. There has been a rapid disappearance of tropical forests in our country also, at a rate of about 0.6% per year. With the current rate of loss of forest habitat, it is estimated that 20-25% of the global flora would be lost within a few years.

2. Poaching

Illegal trade of wildlife products by killing prohibited endangered animals i.e. poaching is another threat to wildlife. Despite international ban on trade in products from endangered species, smuggling of wildlife items like furs, hides, horns, tusks, live specimens and herbal products worth millions of dollars per year continues. The developing nations in Asia, Latin America and Africa are the richest source of biodiversity and have enormous wealth of wildlife. The trading of such wild life products is highly profit making for the poachers who just hunt this prohibited wild life and smuggle it to other countries mediated through a mafia. The cost of elephant tusks can go upto $ 100 per kg; the leopard fur coat is sold at $ 100,000 in Japan while bird catchers can fetch upto $ 10,000 for a rare hyacinth macaw, a beautiful coloured bird, from Brazil.

3. Man-wildlife conflicts

Instances of man animal conflicts keep on coming to lime light from several states in our country. In Sambalpur, Orissa 195 humans were killed in the last 5 years by elephants. In retaliation the villagers killed 98 elephants and badly injured 30 elephants. Several instances of killing of elephants in the border regions of Kote-Chamarajanagar belt in Mysore have been reported recently. The man-elephant conflict in this region has arisen because of the massive damage done by the elephants to the farmer's cotton and sugarcane crops. The agonized villagers electrocute the elephants and sometimes hide explosives in the sugarcane fields, which explode as the elephants intrude into their fields. In fact, more killings are done by locals than by poachers. Recently, in early 2004, a man-eating tiger was reported to kill 16 Nepalese people and one 4-year old child inside the Royal Chitwan National Park, 240 Km South-west of Kathmandu. The Park renowned for its wildlife conservation effort has become a zone of terror for the locals.

Conservation of Biodiversity

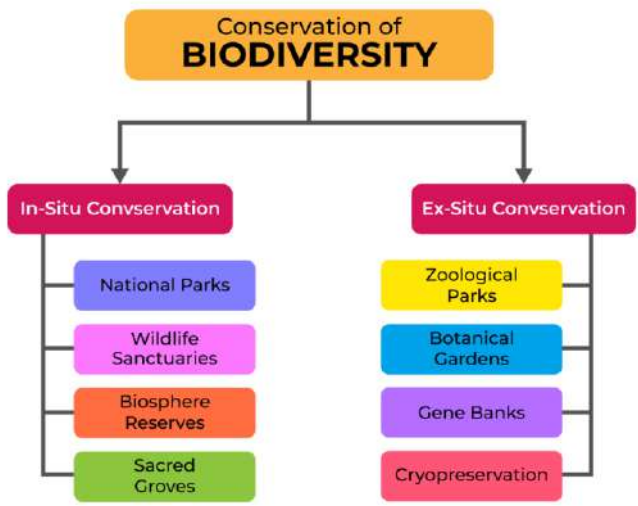


Figure 4: Showing various types of conservation of biodiversity (Source: https://www.geeksforgeeks.org/in-situ-and-ex-situ-conservation-of-biodiversity/)

The enormous value of biodiversity due to their genetic, commercial, medical, aesthetic, ecological and optional importance emphasizes the need to conserve biodiversity. Gradually we are coming to realize that wildlife is not just a game to be hunted, rather it is a gift of nature to be nurtured and enjoyed. A number of measures are now being taken the world over to conserve biodiversity including plants and wildlife. There are two approaches of biodiversity conservation: (a) In situ conservation (within habitat): This is achieved by protection of wild flora and fauna in nature itself. e.g. Biosphere Reserves, National Parks, Sanctuaries, Reserve Forests etc. (b) Ex situ conservation (outside habitats) This is done by establishment of gene banks, seed banks, zoos, botanical gardens, culture collections etc.

In Situ Conservation

At present we have 7 major Biosphere reserves, 80 National Parks, 420 wild-life sanctuaries and 120 Botanical gardens in our country covering 4% of the geographic area.

- The Biosphere Reserves conserve some representative ecosystems as a whole for long-term in situ conservation. In India we have Nanda Devi (U.P.), Nokrek (Meghalaya), Manas (Assam), Sunderbans (West Bengal), Gulf of Mannar (Tamil Nadu), Nilgiri (Karnataka, Kerala, Tamil Nadu), Great Nicobars and Similipal (Orrisa) biosphere Reserves. Within the Biosphere reserves we may have one or more National Parks. For example, Nilgiri Biosphere Reserve has two National Parks viz.Bandipur and Nagarhole National Park.
- A *National Park* is an area dedicated for the conservation of wildlife along with its environment. It is also meant for enjoyment through tourism but without impairing the environment. Grazing of domestic animals, all private rights and forestry activities are prohibited within a National Park. Each National Park usually aims at conservation specifically of some particular species of wildlife along with others. Some major National Parks of our country are enlisted in the Table below:

Table 4: Some important National Parks in India

Name of National Park	State	Important Wildlife
Kaziranga	Assam	One horned Rhino
Gir National Park	Gujarat	Indian Lion
Dachigam	J & K	Hangul
Bandipur	Karnataka	Elephant
Periyar	Kerala	Elephant, Tiger
Kanha	M.P.	Tiger
Corbett	U.P.	Tiger
Dudwa	U.P.	Tiger
Ranthambore	Rajasthan	Tiger
Sariska	Rajasthan	Tiger

Source: Ecology Research (Vol. 2, p. 99) by Annapurneshwari. H, 2021. Edited by AA Kengar, MS Darade, KS Vinayka, BK Das, JV Mallia, S Chahande published and copyright reserved by Bhumi Publishing, 2021

- Wildlife sanctuaries are also protected areas where killing, hunting, shooting or capturing of wildlife is prohibited except under the control of highest authority. However, private ownership rights are permissible and forestry operations are also permitted to an extent that they do not affect the wildlife adversely.

For plants, there is one gene sanctuary for Citrus (Lemon family) and one for pitcher plant (an insect eating plant) in Northeast India. For the protection and conservation of certain animals, there have been specific projects in our country e.g. Project Tiger, Gir Lion Project, Crocodile Breeding Project, Project Elephant, Snow Leopard Project etc. Ex situ Conservation: This type of conservation is mainly done for conservation of crop varieties, the wild relatives of crops and all the local varieties with the main objective of conserving the total genetic variability of the crop species for future crop improvement or afforestation programmes.

In India, we have the following important gene bank/seed bank facilities:

i. National Bureau of Plant Genetic Resources (NBPGR) is located in New Delhi. Here agricultural and horticultural crops and their wild relatives are preserved by cryo-preservation of seeds, pollen etc. by using liquid nitrogen at a temperature as low as -196°C. Varieties of rice, pearl millet, Brassica, turnip, radish, tomato,

onion, carrot, chilli, tobacco, poppy etc. have been preserved successfully in liquid nitrogen for several years without losing seed viability.

ii. National Bureau of Animal Genetic Resources (NBAGR) located at Karnal, Haryana. It preserves the semen of domesticated bovine animals.

iii. National Facility for Plant Tissue Culture Repository (NFPTCR) for the development of a facility of conservation of varieties of crop plants/trees by tissue culture. This facility has been created within the NBPGR. The G-15 countries have also resolved to set up a network of gene banks to facilitate the conservation of various varieties of aromatic and medicinal plants for which India is the networking co-ordinator country.

Ecosystem Management

Ecosystem management is an approach to natural resource management that aims to ensure the long-term sustainability and persistence of an ecosystems function and services while meeting socioeconomic, political, and cultural needs.

Sustainable development

Sustainable development can be defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

- In other words, it is improving the quality of life of the present generation without excessive use or abuse of natural resources, so that they can be preserved for the next generation.
- The term was first coined in 1972 at the United Nations Conference on Human Environment at Stockholm.
- The most important piece of writing on Sustainable development is in the publication by the World Commission on Environment and Development (WCED) in 1987 titled Our Common Future".
- Sustainable development is often referred as the marriage of economy and ecology. i.e. to attain economic development without compromising the ecological balance.

- It can be attained by rigorous policy change, taking action and altering practices.

There are three aims of sustainable development: -

a) Economic- to attain balanced growth b) Ecological- to preserve the eco system c) Social-guarantying equal access to resources to all human communities.

Need for sustainable development:

- There are several challenges that need attention in the arena of economic development and environmental depletion.
- Hence the idea of Sustainable development is essential to address the following issues.
- To curb or prevent the environmental degradation
- To ensure a safe human life
- To check the exploitative technology and find alternative sources
- To check the over exploitation and wastage of natural resources
- To regenerate renewable energy resources

Components of sustainable development

The components are broadly divided into three elements namely social, economic and environmental:

Social components

• Workers health and safety

• Impact on local communities, quality of life

• Benefits to disadvantaged groups

Economic components

• Creation for new markets and opportunities for sale growth

• Cost reduction through efficiency and improvements and reduced energy and raw material inputs

• Creation of additional value

Environmental components

- Reduce waste, effluent generation, emission into environment
- Reduce impact on human health
- Use of renewable raw material
- Elimination of toxic substances

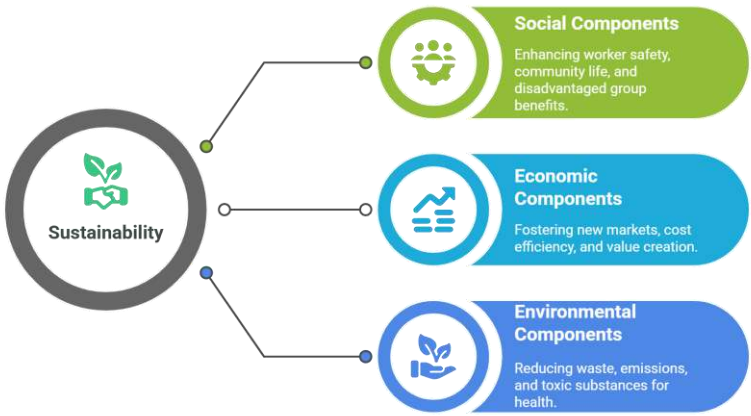


Figure 4: Components of sustainable development

Goals of Sustainable development

- The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity.
- The 17 SDGs are integrated—they recognize that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability
- Countries have committed to prioritize progress for those who're furthest behind. The SDGs are designed to end poverty, hunger, AIDS, and discrimination against women and girls.

- The creativity, know how, technology and financial resources from all of society is necessary to achieve the SDGs in every context.

Conclusions

It is imperative that the phenomenon of biodiversity is very vast, complex and interdependent and there is no single over-arching effect of diversity on either productivity or stability. However, it has become obvious that biodiversity is indeed important for both managed and natural ecosystems, though the relative contributions of diversity and composition remain unclear. If current human growth and resource management patterns do not change, it is likely that we will lose many important species, and the ecosystems of the world may never recover. Human is only one more of natural creatures and should not be alien to the other life-forms. We have no moral right to destroy nature and other beings that dwell on earth. We should treat all animals and plants with compassion. Every individual can make a small and yet significant effort in the race to save our planet and conserve biodiversity.

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CHAPTER-10

BIODIVERSITY CONSERVATION AND ECOSYSTEM MANAGEMENT

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Abstract

Centre of Science and Environment's new report entitled 'State of India's Environment 2021 stated that there are a total four biodiversity hotspots found in India and 90% of their area has been lost. Further, a drop in carbon retention services or carbon sequestration has been registered in total 14 states/ UTs of the Country. Such a decline in such types of services clearly indicates a drop in the capture tendency of carbon dioxide from the atmosphere. For India, conservation of biodiversity tends to be quite crucial also because it is directly linked with providing livelihoods and improving socioeconomic conditions for many of its inhabitants, thereby contributing to sustainable development and poverty alleviation. Conservation of biodiversity should be considered as a national priority and incurring expenditure for this will be a long-term investment for securing our own wellbeing. The principles and guidelines provided for ecosystem-based management are equally valid for large-scale projects on infrastructure development and for smaller scale conservation and development projects.

Keywords: Biodiversity, conservation, ecosystem management, ecosystem restoration, ecological services.

Introduction

Convention on Biological Diversity, Rio, (1992) defined Biodiversity as "the variability among living organisms from all sources and the ecological

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complexes of which they are part; this includes diversity within species, between species, and of ecosystems."

Loss of biodiversity causes global food security problems, hasten grassland degradation, and causes water and soil pollution. Undoubtedly, climate change is the biggest culprit for a loss of biodiversity. During 21st century, the effects of climate change mainly driven by human activities on biodiversity loss have significantly increased. Human activities have affected around 75 % of terrestrial ecosystems and 66 % of the marine environment which have lead to 25 % of the world's species threatened with extinction. Additionally, social and economic development like urbanization, industrialization, and agriculture expansion, significantly alter land use pattern and cover, promoted deforestation, habitat fragmentation, and soil deprivation (Wang et al., 2024).

Value of biodiversity

It has immense value to society and it forms the basis of a wide range of ecosystem services that are essential to humankind. The total global value of such services has been estimated to be $33 trillion per annum, which equates to 1.3 times the global GDP (Costanza et al., 1997). However, it is important to recognize that biodiversity benefits people through more than just its contribution to material welfare and livelihoods; it also contributes to security, resiliency, social relations, health, and freedom of choices and actions (Tucher, 2005).

As per the reports of MEA (2005) the biodiversity impacts have substantial social and economic consequences because they result in the degradation of ecological services. The MEA found that of the 24 ecosystem services assessed, 15 (or 60%), are being degraded. These changes will also be intensified by the loss of genetic diversity, which will affect the ability of ecological communities to resist or recover from disturbances and environmental change, including long-term climatic change. Food, genetic resources, fresh water services has been degraded. In all the regulating services like; pollination, air quality, water, soil, climate, pest and natural hazards, the regularization get affected. In addition, the cultural services including education knowledge, social-aesthetic values, recreation and tourism have also faced degradation.

The Global Biodiversity Crisis

Due to non eco-friendly human activities, biodiversity is being lost and degraded at an unprecedented rate. In spite of having so many reasons to conserve biodiversity (moral, cultural, economic reasons) and its ecosystem

services, we fail to conserve it in equal rates as in pace we lost it. International team of experts under the Millennium Ecosystem Assessment – MEA (2005) assessed in details the condition of world's ecosystems. In the concluding remarks it was mentioned that "Human actions which are mostly irreversible to nature are responsible for drastic changes in loss of biodiversity on earth. Over the past 50 years the changes in biodiversity components become more rapid than reported in any time of history.

The key findings of MEA, 2005 assessment are as follows:

- Practical evidences showed that transformation of all Earth's ecosystems is due to human actions.
- Although globally, the net rate of conversion of some ecosystems has begun to slow, in some instances this is because little habitat remains for further conversion.
- The population size or range of the majority of species is declining across a range of taxonomic groups.
- Human's impacts have amplified species extinction rates 1,000 times over the past few hundred years additionally in Earth's history.
- The species distribution on Earth is now become more homogenous.
- According to IUCN (World Conservation Union criteria for threats of extinction), 10% to 50% of well-known higher taxonomic groups of plants and animals are currently under the category of threatened with extinction.
- Domesticated species also shows trends of decline in genetic diversity at global level.

Conservation Projects

For Addressing biodiversity loss, habitat conservation, and ecosystem restoration, there is an urgent need to plan strategies for preserving biodiversity hotspots, enhancing ecosystem services, and promoting ecological resilience. It includes Biodiversity monitoring techniques, conservation biology research, and community-based conservation initiatives. Protecting biodiversity is essential for maintaining ecosystem functions, supporting food security, and enhancing climate resilience. Achieving global biodiversity targets and promoting sustainable land use practices, and preserving natural heritage so that future generations can get benefit.

Ecosystem management is an approach that concerned with restoration of healthy ecosystems and sustaining their functions and values. Sustainability of any ecosystem depends on preserving conditions or on the flexibility of organisms in varying circumstances. The ecosystem is a complex entity comprises of a co-dependent interrelated biotic and abiotic components.

Ecosystem management requires a jointly developed idea of desired future ecosystem with setting that put together all powering factors like ecological, economic, and social. It must be under ecological, not political boundaries. Different ecosystems diverge from each other in the quantity of solar energy they carry, in the form of food, heat, and water available for different living organisms- microbiota, plants, and animals in the system. Surrounding climatic conditions keep on vary around the globe which makes microbiota, plants, and animals to evolve and adapt to varied specific environments. Adaptation is the only way out to keep the varied biota in specified given sets of environmental conditions as climate changes or disruptions, change the habitat. It is not possible for every type of Biota to evolve often and rapidly to adapt suitably to keep up with the change and resulting into impaired biodiversity.

Many businesses also fund positive biodiversity conservation or restoration measures that are not directly associated with specific project. Some businesses have the opportunity to manage parts of their property in ways that benefit biodiversity (e.g. buffer zones to mining sites or catchments owned by water companies) or undertake or fund research that can help manage biodiversity more effectively (Tucker, 2005).

One such example is of Northumbrian Water and the UK Highways Agency which have produced Biodiversity Action Plans (BAPs) for all their landholdings. Such actions are often undertaken in partnership with conservation organizations. Various Conservation organizations include governmental agencies, academic institutions and NGOs which provides an important role in encouraging and guiding conservation actions by:

- Monitoring biodiversity and setting protection and action priorities for species, e.g. IUCN Red Data lists (IUCN 2001) and regional threatened species lists (BirdLife International, 2004), habitats (Tucker & Evans, 1997) and sites, e.g. BirdLife's Important Bird Areas (Heath & Evans, 2000).
- Conducting ecological research on species and habitats, to identify the causes of species declines and necessary corrective measures, such as habitat management needs or regulation of species exploitation.
- Planning for conservation e.g. BAPs and site biodiversity conservation management plans (Ramsar Bureau, 2002; Thomas & Middleton, 2003).

Approaches to manage biodiversity

For the management of species communities, there are three principal approaches which may be employed:

- a species approach
- an ecological processes approach
- a landscape approach

But society shift from a resource management model which focuses on single species, to a standard where land strive to preserve the integrity, stability, and beauty of the biotic community. This is clearly more than just a scientific dilemma although natural resource managers are experimenting with new approaches. For exploring the Biodiversity Crisis, there are two things which must be followed for sustainable management of ecosystems: a new set of ethics and a new set of scientific standards (Knight, 1998).

BioVision Africa Founded in 2018 which aims *to* promote workable solutions to a number of our natural resource management challenges with a view of enhancing sustainable development. By running different programs such as chemical waste management, financing loss, damage and climate justice; water resource management; ecosystem and biodiversity conservation; sustainable energy and various campaigns in this regard are the major objectives of this organization.

Recent Trends in Biodiversity Conservation in India

India is an immensely wealthy in terms of species and ecosystem diversity with over 1,03,258 species of fauna and 55,048 species of flora acknowledged in the 10 biogeographic zones of the country. Out of 55,048 known floral species, 12,095 are known to endemic in India. The picture of delicate balance between progress and preservation is raised by the news of Assam's Hollongapar Gibbon Sanctuary. Vedanta-owned Cairn created recent controversy by proposal of drilling out the Assam's Hollongapar Gibbon Sanctuary. This project will threaten the habitat of Hoolock Gibbon- an endangered species in India. It is a big challenge for India that the country's only ape species occupying the border area fails in meeting the development needs with biodiversity conservation (Reimagining Biodiversity Conservation in India, 2024).

A millions of people in India are residing in the neighborhood of protected areas which produces major challenges for the saviors of biodiversity. It is because of the reason that the protected areas to some extent are occupied and targets of major conservation efforts for organisms (including elephants, tigers, leopards, bears, wolves, snow leopards, wild pigs, nilgai, chital, & sambar) pose threats to humans, livestock and crops. Such challenges are likely to become more widespread across the world. Approximately 15% of global land and 5% of its India's land has been protected officially (Mousumi Ghosh-Harihar et al., 2019).

As per Jackson and Sutherland (2013) *Ex situ* conservation has several purposes -

- Rescue of threatened/ endangered germplasm
- Production of material for reintroduction, translocation, reinforcement, habitat, and landscape restoration and management
- Produce material for conservation biology research.
- Collection of germplasm for storage in various forms of ex situ facility
- Supply material for various purposes to reduce pressure from wild biota
- More growing of species with recalcitrant seeds
- Generation of skills and knowledge to support wider conservation aims
- Make material available for conservation, education and display

Ex situ Conservation of Biodiversity

Biodiversity consists of variety and variability of all forms of life on earth which is essential for human existence. There are two basic and complementary ways to restore lost and degraded biodiversity called in situ and ex situ conservation means. Conservation involves its maintenance, sustainable utilization, and restoration. In the ex situ type of conservation, all levels of biological diversity are conserved outside their natural habitats through different techniques like zoo, captive breeding, aquarium, botanical garden, and gene bank. It helps in communicating the issues, raising awareness, and gaining widespread public and political support for conservation actions. Ex situ conservation is quite useful for breeding programs for endangered species in captivity for reintroduction.

- Besides many benefits, certain limitations of ex situ conservation includes-
- protection and maintenance of organisms in artificial habitats
- weakening of genetic diversity
- inbreeding depression
- adaptations to captivity
- accumulation of deleterious alleles

Ethiopia is known to be one of the richest centers of genetic resources in the world. Currently, a number of stakeholders/ actors are actively working on biodiversity conservation through ex situ conservation strategies by establishing gene banks, botanical garden, and zoo (Kasso & Balakrishnan, 2013).

Ecosystem Management

"Ecosystem management" focused mainly on elements of landscapes and aims to manage for the long-term integrity of whole ecosystems. Ecosystem management includes the combination of social and ecological data and the application of the principles of adaptive management.

According to Lertzman et al. (1997) ecosystem management must be well organized and should be based on theme which was originally formulated in 1994 by Grumbine.

- Hierarchical context: All the levels in the biodiversity hierarchy such as genes, species, populations, ecosystems and landscapes must be considered and managers must seek connections among all levels.
- Ecological boundaries: It requires working across administrative and political boundaries and ecological boundaries at appropriate scales.
- Ecological integrity: Protection of all elements of native diversity and the ecological processes and patterns that maintain it.
- Data collection: It requires more information about natural systems.
- Monitoring: The proper monitoring of decisions and actions must be tracked in order to evaluate success or failure.
- Adaptive management: Our management actions are experiments that must be designed, monitored, and used to change future management.
- Interagency cooperation: It is not a single agency and managers and others have to work together to integrate conflicting mandates and management goals.
- Organizational change: To keep it real requires diverse changes in institutional structure and behavior that range from minor to fundamental.
- Humans as part of nature: People and their actions cannot be separated from nature. Their mutual influences on each other must be recognized.
- The importance of values: Human values play a fundamental role in determining our goals for managing ecosystems.

Ecosystem Restoration and Management based on Nature-based Solutions

In response to disturbing issues of climate change, food and water insecurity, natural disasters, human health, and economic and social development, the Nature-Based Solutions have emerged as a holistic and transformative approach. It integrates conservation, restoration, and sustainable

development, with a flexible pathway to balance ecosystem conservation with development of society (Cheng et al., 2024.)

As per Dick et al. (2020) the natural solutions significantly contributes to achieving the target by 2030 Sustainable Development Goals (SDGs) such as SDG 2 (food security), SDG 3 (health and well-being), SDG 6 (clean water and sanitation), SDG 11 (sustainable cities and communities), SDG 13 (climate action), SDG 14 (life below water), and SDG 15 (life on land).

IUCN crafted its definition with a global perspective in mind, considering various ecosystems but primarily emphasizing the protection and management of natural ecosystems, including forests, Theoretical framework for ecosystem restoration based on grasslands, freshwater, peat lands, farmlands, and oceans.

Ecological Restoration Methods

For biodiversity conservation various ecological restoration methods can be used as proposed by SER, the Society for Ecological Restoration in 2004.

(1) Natural Regeneration Methods:

- *It works without any type of Intervention*
- *It rely on natural processes*
- *Involves in spontaneous recovery of ecosystems*
- *It works without direct human intervention*

(2) Assisted Regeneration Methods:

- *It belongs to the Conservation and Management with Moderate Intervention type*
- *Human intervention supports the natural recovery of ecosystems*
- *Involved in dispersing seed or creating favorable conditions for native vegetation to thrive*
- *These methods focus on conservation-oriented strategies*

(3) Conservation:

- *It falls under the Conservation and Management with Moderate Intervention type category.*
- *Conservation-oriented restoration*
- *The strategies prioritize the preservation and protection of existing ecosystems*
- *It focuses on maintaining the integrity and safeguard of biodiversity*

Main Challenges for India in Biodiversity Conservation

India with a dreadful score of 45.5 (out of 100) has been ranked 176th in the Global Nature Conservation Index, 2024. India finds its place as one of the

five worst performers alongside Kiribati (180), Turkey (179), Iraq (178), and Micronesia (177) in the ranking of 180 countries (data released on October 24, 2024). It is necessary that the establishment of protected areas must be followed by management changes to ensure recovery of endangered organisms and their habitats. From existing data on protected areas it is clear that it is insufficient and needs the proper the gazetting. One of the major utilization of establishment of PAs is their subsequent conservation efforts which lead to a successful tiger and other wildlife species conservation efforts (Gubbi et al., 2017).

Recent advances in Biodiversity Conservation

Due to an alarming level of Global climate change, the overexploitation of natural ecosystems resulting in decline of species number, there is an urgent need to change our environmental policies (MEA, 2005). In Germany, nature conservation has a long tradition and recently a number of international and national strategies to protect biodiversity have been introduced such as UN Statistical Commission adopted the System of Environmental-Economic Accounting- Ecosystem Accounting as a milestone (Edens et al., 2022). The SEEA EA provides detailed guidance measuring the extent and condition of ecosystems and how to quantify ecosystem services. Previously established environmental economic accounts (EEA) added 'accounting of ecosystems' as a new part to their services. Accounting ecosystem reflects the interrelations such as the environmental impact of the economy, the yields of natural resources and the value of environmental protection measures between the environment and the economy. Nonetheless, there don't feel to have been any major advancement for case in avoiding species disappearance and the loss of terrestrial diversity (Convention on Biological Biodiversity, 2022). Grunewald et al. (2024) believed that both ecosystem data and pointers are appropriate to economic policy and can be used to find solution pathways. Additionally expected that ecosystem accounting will help decision-makers from other policy areas will be motivated to take practical steps in this direction.

Under biodiversity conservation initiatives, India launched the National Biodiversity Strategy and Action Plan (NBSAP) 2024-2030, at the COP 16 to the Convention on Biological Diversity (CBD). India has updated the NBSAP to ally with the Kunming-Montreal Global Biodiversity Framework (KM-GBF) establishing the National Biodiversity Targets (NBTs). This plan made 23 National Biodiversity Targets focusing on reducing threats to biodiversity, ensuring sustainable use of resources, and enhancing tools for implementation. Each target is strategy based aimed at promoting ecosystem resilience, species recovery, and sustainable management practices.

Coordination of biodiversity conservation efforts across India is controlled by a central agency, MoEFCC. Due to the occurrence of 22 agrobiodiversity hotspots in India with around 168 different crop varieties to its credit, the plan listed area-based conservation of agrobiodiversity. Along with this prime importance must be given to the conservation of wetlands, coastal and marine ecosystems, genetic diversity and biosafety, participatory approaches, eco-development, communication and public awareness. As per record over 20% of the country's geographical area is under biodiversity conservation and special attention needs to be given to the management of alien invasive plant species that are impacting native biodiversity.

The continuous decline in biodiversity and loss of environment is mainly attributed to the contribution of undervalued biodiversity studies in decision-making. The biodiversity metrics are generally insufficient to capture the various ecosystem services or welfare attributes important to people. For the assessment of costs and benefits of biodiversity conservation, the application of economic principles and tools may be useful and this approach may also help to improve the further effectiveness and efficiency of biodiversity conservation. Similarly, the Principles of ecology help us in the proper estimation of biodiversity outcomes and benefits of conservation which can be valued economically (Strange et al., 2024).

Biodiversity metrics are used for a broad range of conservation purposes and are also necessary for measuring the impact of conservation projects as well as the adverse effects caused by infrastructure projects, urban development or changed land uses, etc. The two major applications of biodiversity metrics are given as follows:

- Metrics are critical for monitoring and evaluation of ecological trends over time and helps to estimate species decline, predict extinction risks, and to raise awareness regarding conservation needs.
- Metrics are useful in comparing the spatial and temporal distributions of species and ecological communities which tends to be critical for conservation planning and management.

Initiatives Undertaken by India 2024: Ministry of Environment, Forest and Climate Change (Year-end Review, 2024).

- MISHTI was launched on World Environment Day event in 2024 for the restoration of Mangroves. Successfully around 22,561 hectares of degraded Mangroves were restored in 13 States/UTs and 17.96 Crore rupees released for the restoration of 3,836 hectares in 6 States/UTs.

- Under National Clean Air Programme (NCAP) 40% particulate matter reduction is achieved in 23 cities and 11,200 Crore rupees fund allocated for Pollution Control. For monitoring of air quality, PRANA Portal was launched.
- Number of Tiger Reserves in India upgraded to 57 and two New Tiger Reserves Notified in 2024 namely, Guru Ghasidas-Tamo Pingla Tiger Reserve and Ratapani Tiger Reserve.
- An initiative was implemented by the Wildlife Institute of India (WII) in collaboration with the Assam Forest Department and Aaranyak, with funding from the National CAMPA Authority. Under this, first-ever Ganges River Dolphin tagging was done in Assam which is considered as significant milestone in advancement of Dolphin project.
- Conservation planning in India is based on identifying and protecting wild habitats across all the ecosystems. The number of protected areas (PAs) in the country has risen from 745 to 1022 which accounts for 5.43% of the country's total geographic area. There has been a substantial increase in establishment of Community Reserves. The numbers of Community Reserves in the country has increased from 43 (year 2014) to 220 as on date.
- Apart from this, the country also has 57 tiger reserves notified under the Wild Life (Protection) Act, 1972. States have also declared 33 elephant reserves for providing safer habitats to the elephants.
- In the meeting of National Centre from Sustainable Coastal Management (NCSCM) on 4.9.2024 under the Chairmanship of the Minister for Environment, Forest and Climate Change, a Digital copy of Mangrove Zonation atlas was released.
- A total of 13 beaches across 6 States and 3 Union Territories have been certified with Blue Flag Certification for the season 2024-2025.
- Green Climate Fund has prepared an Adaptive Management Plan for externally aided Enhancing Coastal Resilience of Indian Coastal Communities (ECRICC) project.
- Nagar Van Yojana (NVY) was implemented by National Afforestation and Eco-development Board (NAEB) which prediction of developing 600 Nagar Vans and 400 Nagar Vatikas in the country during the period from 2020-21 to 2026-27. Its objective is to enhance the trees outside forests and green cover, enhancement of biodiversity and ecological benefits to

the urban and peri-urban areas apart from improving quality of life of city dwellers.

Conclusion

Currently the problem of biodiversity loss which now becomes a global issue accelerates our food security problems. Keeping in mind the value of biodiversity to humankind and to environment, we need to frame out some authentic measures to control biodiversity loss. It includes effective conservation actions approached actually instead of only available in country's conservation records. Ecosystem management is such an initiative which focuses landscapes elements and tries to manage long-term integrity of ecosystems. Rehabilitation of 600 square kilometer sweeping valley area with new plantation of 250,000 trees and 1 million shrubs in Saudi Arabia is a great initiative which strives to re-green deserts to tackle drought and land degradation. It is the demonstration of immense potential of cultural capital and traditional wisdom for managing the natural environment. Such approaches are required to be embrace by all across the world with target of minimum of around 5% of global afforestation equal to 200 million hectare of degraded land.

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CHAPTER-11

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN BIODIVERSITY CONSERVATION

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Abstract

The productivity and stability of natural ecosystems depend on the biodiversity and the current rate of loss of biodiversity and ecosystem degradation is unprecedented, particularly in developing nations facing high demographic pressures. Ecosystem degradation and rapid decline in biodiversity is primarily caused by contamination and excessive consumption of resources, habitat loss, deforestation and climate change. It, therefore, becomes essential to monitor and conserve biodiversity for ecosystem restoration but the traditional practices relying on human labour and manual surveys are inefficient to keep pace with the data scale of crisis. The integration of advanced technologies such as Artificial Intelligence (AI), Machine Learning (ML) algorithms in environment sector in recent times has facilitated addressing sustainability challenges through efficient surveillance, administration, preservation of natural resources, generation of optimized plans for ecosystem restoration and biodiversity conservation. The current chapter discusses how the adoption of AI and associated techniques can elevate the conservation efforts for preservation of global biodiversity. The various barriers to worldwide adoption of AI-based systems are also explored in this chapter.

Keywords: Artificial Intelligence, Biodiversity Conservation, Ecosystem, Machine Learning, Sustainability.

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Introduction

Biodiversity is the variety of wide range of earthly life forms, from genetic to ecological level, including genes, populations, species, functions and ecosystems. It entails the ecological, cultural and evolutionary elements that support life in all its forms (McQuatters-Gollop et al., 2019). It is a major indicator of community ecosystem fluctuations and functioning (Tilman et al., 2014); offering us clean water, pollination services, building materials, clothing, food and medicine; in addition to its inherent value and ecological roles (Chaplin-Kramer et al., 2019; Harrison et al., 2014) to provide these basic ecosystem services, it promotes ecological functioning (Whitehorn et al., 2019). The symbiotic relationship that allows humans to co-exist with other living organisms makes the coexistence of humans and nature irreversibly flexible (Arias-Maldonado, 2016). But despite the importance of biodiversity, its conservation is nominally acknowledged. The dichotomy is that our efforts to optimize immediate gains have resulted in reducing biodiversity and endangering the long-term basis for human life (Dasgupta, 2021). Approximately 75% of the land-based territory and 66% of the marine ecology are currently distorted by human intrusions. Also, the globe is currently in a perilous state in terms of the effects of climate change disturbances and global warming (Leahy, 2019). By 2050, the world's last surviving native ecosystems and the species they contain will be under extreme strain due to the need to feed and house world's rapidly expanding human population. If these patterns persist, the radical alteration of the natural world by 2050 may have a catastrophic, permanent effect on humanity from which it may take centuries to recover potentially leading to the degradation and collapse of ecosystems (Chambers et al., 2019; Peterson et al., 1998). Consequently, it becomes imperative to take straightaway action for designing more realistic and effective policies for a sustainable future (Sterner et al., 2019) that help deliver the biodiversity conservation targets under the post-2020 Global Biodiversity Framework (GBF) (Joly, 2022). Sustainable future encompasses interrelated elements of the economy, society and environment (Olawumi & Chan, 2018), and environmental sustainability is the capacity to satisfy the resource and service needs of present and future generations without compromising the ecosystem's health for people (Little et al., 2016). Thus, appropriate monitoring and conservation efforts are necessary to prevent these biodiversity atrocities. Since 1960s, there have been several theoretical and practical frameworks underlying biological conservation (Mace, 2014). The traditional methods reliant on human labour and manual surveys, struggle to keep pace with the data scale of crisis and pose many drawbacks, like introduction of personal bias, slowing data collection, analysis and lack of scalability of approach (Näyhä et al., 2015).

To meet such targets, we need innovative tools facilitating more sophisticated monitoring and that's where modern technology provides a glimmer of hope filling the gaps of traditional methods of data collection and analytics. The 21st century's urgent environmental challenges have brought attention to the need of artificial intelligence (AI), machine learning (ML) and robotics as promising tools for resolving numerous sustainability concerns (MacWilliams et al., 2024). AI is an extensive field that involves the development of systems designed to execute tasks usually associated with human intelligence, including visual perception, speech recognition, decision-making, and language translation. A key area within AI is machine learning, which concentrates on creating algorithms that allow computers to learn from data and make predictions or decisions accordingly (Alotaibi & Nassif, 2024). These tools are making biodiversity assessments more efficient, scalable and cost-effective, thus offering systematic conservation planning (Moilanen et al., 2009) which can lead to substantial economic, social and environmental gains (Bateman et al., 2013).

AI and ML for Biodiversity Monitoring and Conservation

Biodiversity is mostly threatened by over-population, habitat and landscape modification, indiscriminate exploitation of resources, pollution, and lack of proper documentation (Marchese, 2015; Mehring et al., 2020). This, in turn, poses a pessimistic impact on food availability, restricted emission of greenhouse gases, control of invasive species and diseases, etc. (Lampert, 2019; Reid et al., 2019). To address global concerns regarding biodiversity loss, habitat degradation and climate change, the need for innovative and efficient methods to monitor and protect ecosystems has become paramount. Artificial Intelligence (AI) and Machine Learning (ML) are at the forefront of innovative solutions, revolutionizing biodiversity conservation and providing new tools to protect our planet's precious biodiversity.

AI and ML for Biodiversity Monitoring

Monitoring program is the recurring practice of collecting and evaluating data about a species and is central to the objective of conservation. In order to meet the monitoring mandates, conservation biologists must efficiently identify animal and plant populations, and carry out long-term demographic studies which depend on field observations. Over the years, the enhancement of computing power and deep learning has significantly improved the intelligence and reliability of mapping and monitoring techniques. Contemporary machines are now capable of processing larger datasets and more intricate models than ever before (M. Y. Chen et al., 2020). Researchers have intensified their efforts to develop various AI solutions utilizing machine learning to safeguard the Earth for future generations. The integration of

drones equipped with high-resolution cameras and sophisticated sensors, along with AI algorithms, has proven effective in gathering environmental data from inaccessible regions (McLeod & Salm, 2006), thereby expanding human exploration into areas that are otherwise challenging to navigate. This has led to the discovery of new species and forms of life (fig. 1). In many studies, the application of AI-driven methods has enabled machines to automatically recognize, classify, and detect images, sounds, and behaviours

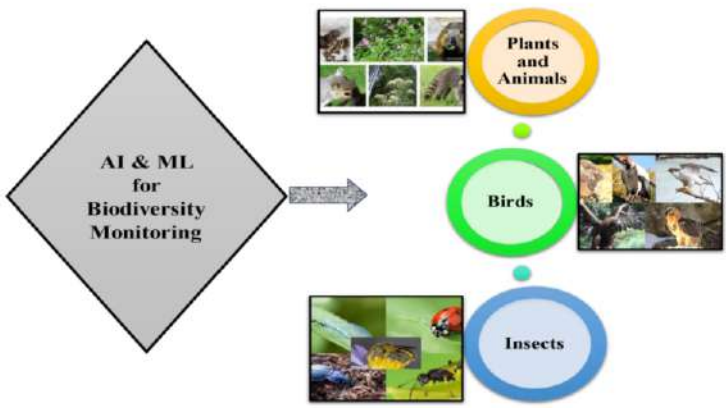


Fig 1: An outline of new life forms of biodiversity detected and monitored by AI & ML

of various organisms, including plants, animals, birds, and insects (Abeßer, 2020; Jimenez-Pitre et al., 2024).

Plants and Animals

The identification of individual plant and animal species is crucial for wildlife monitoring and estimating population sizes, especially for endangered species. In traditional surveys, accurately accounting for the probability of detecting individual species is essential for reliable abundance estimates (Alexander et al., 2012; Royle & Dorazio, 2006). Variations among individual personnels, influenced by demographic characteristics, behaviours and habitat preferences, can introduce biases that lead to inaccurate population counts

when employing conventional survey techniques (Biro, 2013). The incorporation of AI-driven systems for wildlife surveys has gained an exponential increase from the last two decades due to logistical costs, increased count accuracy, improved operational efficiency and lower risk of human injury as compared to ground or other aerial audits (VV et al., 2024). The AI-enhanced acoustic monitoring has revolutionized and automated the detection and classification of wildlife sounds, significantly reducing the time and effort needed to manually analyse extensive audio datasets (Digby et al., 2013). This method is a powerful tool for wildlife conservation since it offers a non-intrusive means of tracking wildlife populations and may be used to learn more about species that are hard to view directly, such as nocturnal, elusive, or remote species (Sharma et al., 2023). Additionally, it makes it possible to gather data continuously, giving a dynamic picture of ecological changes over time (Srinivas Bobba et al., 2024). Further, the AI tools also assist in developing comprehensive strategies for prevention and control of Invasive alien plants (IAPs) which are considered greatest global threats to biodiversity and ecosystem by making rapid, accurate and effective monitoring (Qian et al., 2020). Large-scale data sets collected from the aforementioned technologies enable deep learning models to discover new patterns that are easier for researchers to understand and analyse, which lead to better management solutions (R. Chen et al., 2019). The automation of both image collection and processing reduces the need for human intervention. AI technology is doing wonders, not only on the land, but, also in the water. In marine ecosystems, robotics powered by AI has paved the way for autonomous underwater vehicles (AUVs) which identify species and ML algorithms monitor marine mammal populations by tracking behavioural patterns (Dogan et al., 2024). The temporal and spatial coverage of biodiversity surveys expand manifolds using AI for species identification as it enhances accuracy, reduces errors, and guarantees that massive amounts of data can be handled rapidly.

Birds

Birds are the crucial ecological indicators because of their susceptibility to environmental stressors, making it essential to monitor them effectively. Researchers may collect massive datasets using camera traps over long periods of time and across several sites, but the manual collection and analysis of these data is a significant bottleneck that delays the implementation of timely conservation initiatives. Moreover, monitoring of birds presents a challenge when it comes to rare or migratory species as these species are often elusive, inhabit diverse and inaccessible regions, and display

behaviours that complicate identification. This issue gets worse in situations when differentiating between similar species is essential for focused conservation initiatives (Norouzzadeh et al., 2018). AI-generated data presents a transformational potential in this regard, bridging critical data gaps, and enabling development of robust and precise recognition system. The AI-enabled classification systems accelerate the data processing and delivers timely, actionable information, enabling conservationists to intervene quickly which is crucial for species who are threatened by predation and habitat loss (Akçay et al., 2020).

Insects

Insects play crucial roles in ecosystems, acting as pollinators for crops and wild plants, predators of crop pests, decomposers, seeds dispersers and bioindicators of health of water bodies. Among the numerous threats to biodiversity, the rapid plunge in insects' population is quite distressing which convenes for their conservation in order to maintain ecosystem stability. The conservation can only be possible with accurate species identification, and adequate spatial and temporal data covering insect species populations. But owing to their small size and nocturnal behaviour, insect monitoring has historically been restricted, making their studies challenging with conventional methods (Welti et al., 2021). These difficulties are currently being overcome by AI-assisted image-based automated insect monitoring systems (Chiavassa et al., 2024), where scalable solutions have been designed for monitoring moths and other phototactic insects, whose populations are especially vulnerable to habitat loss and climate change (Roy et al., 2024). Integrating AI techniques across various regions for comprehensive assessment of insect abundance and biodiversity can help to standardize data collection and minimize the required effort (Van Klink et al., 2022).

AI is not only revamping the practice of monitoring known species but also the way of discovering newer ones. An estimated 8 million species remain unidentified (Wilson, 2018). By merging convolutional neural networks (CNNs) with multiangle photography, ML algorithms offer an inventive approach for the identification of possible new species; the system analyses a specimen's morphology from various perspectives (Lu et al., 2024). Researchers can easily discern between known and unknown or 'new' species with AI-generated 'barcode'. A process that previously required months or years of taxonomic examination can now be finished in a fraction of the time.

AI-based techniques have demonstrated that biodiversity can be improved even at its early stage by lowering animal extinction, allowing for more

thorough and extended monitoring of different life forms, opening up previously uncharted territory, and making species classification quicker and simpler. If handled properly, these solutions can have a significant impact on protecting the earth and its resources (Silvestro et al., 2022).

AI and ML for Biodiversity Conservation

These technologies offer a range of tools for fostering sustainable coexistence between humans and nature, and have emerged as powerful allies for communities engaged in conservation efforts. Their role is gradually growing in biodiversity conservation and some of their key roles (shown in fig. 2) are discussed in the following sections.



Fig 2: An overview of application of AI & ML in Biodiversity Conservation

Addressing Challenges of Forest Mapping, Deforestation and Aiding Afforestation

About 30% of the world's land area is made up of forests, which are the primary terrestrial ecosystems that support 90% of all terrestrial species (Shvidenko et al., 2005). Forests are essential for the survival of life on Earth as they absorb up to 2 billion tons of CO_2 emissions in a year and stabilize greenhouse gasses in the atmosphere, resulting in clean, breathable air. In addition to being a significant source of medicinal plants, they contribute

significantly to the world's food security. Yet, despite the advantages that forests offer, they are rapidly degrading all across the world as a result of urbanization, agricultural growth and timber extraction. In order to identify the variables causing deforestation and map the areas where future forest loss is most likely to occur, AI and ML algorithms in conjunction with spatial analysis have been employed to predict and track deforestation rates worldwide (Dominguez et al., 2022; Mayfield et al., 2020). Various organizations use the data recorded by the AI systems for estimation of resource-efficient production and consumption of wood products to guide conservation programs; this data includes information about tree height, type, diameter, wood mass, wood species and wood quality. This technology makes it possible to quickly track the precise locations of trouble spots, determine ideal planting conditions, facilitate quicker seed dispersal and furnish essential nutrients to aid in germination. Digital intelligence and automation powered by AI have the potential to transform manual reforestation techniques in deforested areas and encourage the planting of 1.2 trillion additional trees worldwide (Bastin et al., 2019). The near-real-time information about forest activities and conditions provided by IoT (Internet of Things) devices, is used to develop predictive models for identifying and getting insights into forest health and threats like drought, wildfires, pests, diseases outbreak, soil health, storm damage and other forest disturbances (Shivaprakash et al., 2022). Thus, by leveraging AI, stakeholders can collect inventory data, predict forest hazards patterns, optimize and monitor mass-scale reforestation efforts with unprecedented accuracy and efficiency thereby improving the way we can manage forests and conservation activities.

Tracking Illegal Logging

Illegal logging is pervasive and affects nations with abundant forest resources, including Brazil, Indonesia and the Democratic Republic of the Congo. According to Interpol, the illegal timber trade is worth USD 51 to 152 billion annually “Forestry Crime”.

Illegal logging not only escalates deforestation, disrupts ecosystems and causes economic losses, but it also poses a threat to many rare tree species. AI and IoT can greatly improve the detection and prevention of illegal logging by enabling the monitoring of logging events even in areas with high cloud cover and assisting in the establishment of efficient forest surveillance. AI and ML algorithms analyse large datasets, find patterns and detect anomalies in timber trade data, alerting authorities to illegal activities. These advanced technologies not only offer precise and timely detection but also provide extensible solutions that can be implemented across large and remote forest

areas ensuring sustainability of forest resources and preservation of biodiversity (Ramadan et al., 2024).

Wildlife Poaching Prevention

Poaching of wildlife, particularly endangered species, is a serious threat to biodiversity worldwide. Establishing ranger posts and constant human patrolling are the traditional preventive measures but these are insufficient from the viewpoint of non-deployments at inaccessible geographical regions and safety issues where hundreds of rangers have been killed by poachers. AI and ML play a key role in assisting law enforcement to take smarter approach to tracking poachers. AI-powered surveillance systems are being deployed in protected areas that signal alert to agencies in real-time when poaching activity is detected (Fang et al., 2017).

Aquatic & Marine Biodiversity and Water Resource Conservation

The applications of AI in aquatic and marine biodiversity and water resource optimize the conservation of aquatic and marine flora and fauna and water resources. AI and ML models, for instance, have been used to forecast real-time streamflow (Krajewski et al., 2021), water quality (Wang et al., 2021), water pollution and toxicology (Banaee et al., 2024; Duan et al., 2024), aquatic and marine biodiversity health monitoring, extinction, and conservation (Ditria et al., 2022; Singh et al., 2024). These predictions have been crucial in paving the way for development of new technologies revealing new facets of water resource management and conservation.

Sustainable Resource Management (SRM)

AI and ML have revamped and revolutionized SRM by offering creative solutions that maximize the use of natural resources, control energy and cut waste while the world's resource demand keeps rising (Jones et al., 2024). AI-powered smart grids maximize the use of renewable resources and minimize the need for backup power from non-renewable sources (Khan et al., 2023), reduce greenhouse gas emissions (Díaz-Rodríguez et al., 2023), and lessen dependency on fossil fuels by using real-time data to better balance energy supply and demand. By improving the sorting of recyclable materials and increasing recycling processes' efficiency, ML algorithms are lowering the quantity of garbage that ends up in landfills, lessening the environmental impact of waste disposal, and preserving ecosystem balance.

Ecohydrology Predictions

Ecohydrology integrates key elements of the Earth system, including vegetation, microorganisms, aquatic life, soils, atmosphere, and both surface and subsurface hydrology. This field of research serves as a bridge between ecosystem ecology and the science of the water cycle, drawing upon insights from land surface processes, plant physiology, atmospheric science, and hydrology (Guswa et al., 2020). While advancements in medium-range weather forecasting and seasonal-to-interannual climate predictions have been notable, the uncertainties in predictions related to land-atmosphere interactions have escalated, contributing to an increasing margin of error in simulations. The application of AI and ML techniques has introduced new avenues for deriving mechanistic understanding from the vast array of data available across different scales. These approaches aim to mitigate uncertainties in ecohydrology by linking plant physiology and hydraulics, as well as soil composition and dynamics, to soil moisture and extreme water cycle events, thereby enhancing the predictability of flood and drought risks (Hoffman et al., 2021).

Habitat Mapping

AI and ML have proven to be essential for habitat mapping and restoration, particularly for marine ecosystems, which are difficult to map. AI algorithms and satellite imagery are used to create detailed maps of marine ecosystems, evaluate habitat changes over time, identify areas that require conservation, and forecast ecological trends. Using this approach helps create well-informed conservation plans. Furthermore, it promotes a more sustainable interaction between human activities and marine ecosystems by making it easier to incorporate scientific knowledge into choices about resource administration and policy making (Mahdavi et al., 2024).

Barriers to Adoption of AI-Based Systems for Biodiversity Conservation

Inadequate Awareness

Due to the inherent complexity of these new technologies, there is often a lack of awareness and interest among stakeholders on the availability and applicability of technologies. Consequently, one of the most crucial steps in

implementing these technologies in the field is to increase stakeholders' capacity for their proper usage. Effective case studies and pilot projects are crucial for fostering comprehension and setting reasonable expectations.

Data Quality and Availability

High-quality, comprehensive datasets are essential for training accurate AI models. In many regions, data on wildlife populations and habitats are sparse or unreliable, limiting effectiveness of AI applications. This creates hurdles for stakeholders to make informed decisions on biodiversity, jeopardising the efforts to conserve, restore and sustainability manage nature.

Ethical Considerations

The use of AI to biodiversity conservation brings up ethical issues, such as the possibility of abuse of surveillance tools or the effect of drone monitoring on animal behaviour. Therefore, extra precautions must be taken when deploying such technologies in places with particularly vulnerable communities, such as indigenous groups or communities that depend on forests. It is necessary to define and adhere to concepts like data security, free, prior, and informed consent, and allowed applications. Conservationists must carefully consider these issues and develop guidelines to ensure adequate AI use.

Limited Suitability to Harsh Field Conditions

Technologies that are deployed must possess sufficient robustness to operate effectively across various timeframes and withstand the challenging conditions encountered in the field. Key obstacles for these technologies include adverse climatic and weather conditions, as well as potential damage from animals and acts of vandalism. Additionally, the lack of adequate supporting infrastructure, such as unreliable connectivity, further constrains their operational dependability.

Limited Commercial Scalability

The absence of a robust market constrains the investments available in the sector, which subsequently hampers scaling efforts and inhibits the creation of user-friendly interfaces for practitioners.

Uncertainties Associated with AI

Though, AI technology has potential applications in forestry and biodiversity conservation, but because of the uncertainty associated with data, the predictions made by AI and ML models may not be always reliable.

Conclusions

Environmental resilience is fundamentally linked to the conservation and enhancement of biodiversity across various levels, from local ecosystems to the global biosphere. The integration of AI and ML in the monitoring and safeguarding of natural ecosystems presents a promising pathway for enhancing environmental conservation initiatives. By leveraging these technologies synergistically, we can make substantial progress in tackling the complex issues that threaten biodiversity and ecosystem health. These tools enable the identification of critical areas for conservation, evaluation of human impact, and direction of habitat restoration efforts, thereby supporting a data-driven approach to preserving our planet's biodiversity for a sustainable future. This proactive strategy can yield more effective conservation results, such as the protection of endangered species, rehabilitation of damaged habitats, and reduction of human-wildlife conflicts. Furthermore, these technologies facilitate proactive measures, allowing us to address the effects of environmental degradation before they reach an irreversible stage. Nonetheless, the broad implementation of these technologies in conservation faces several challenges. Issues such as regulatory limitations, privacy concerns, technical constraints, and the necessity for capacity building and training pose significant obstacles. Overcoming these challenges will necessitate collaboration among governments, conservation organizations, researchers and technology developers to establish comprehensive frameworks, guidelines, and standards for their responsible use in environmental monitoring and protection.

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CHAPTER-12

LEISHMANIASIS AND SUSTAINABLE HEALTHCARE: ADDRESSING NEGLECTED TROPICAL DISEASE

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Abstract

This book chapter focuses on neglected tropical disease leishmaniasis which is responsible for the destruction of human health and cause severe infection if not treated with the appropriate drugs. So, the diagnosis of any infection is a very important role in tropical diseases. The *Leishmania* infection is caused by protozoan parasite of genus *Leishmania*. Leishmaniasis is a parasitic infection found in tropics, subtropics, and southern Europe. It is classified as a neglected tropical disease (NTD). Leishmaniasis is caused by infection with Leishmania parasites, which are spread by the bite of phlebotomine sand flies. More than two-thirds of these cases are reported in six countries, including Afghanistan, Algeria, Brazil, Colombia, Iran, and Syria. Over 90% of new cases of visceral leishmaniasis occur in 6 countries: Bangladesh, Brazil, Ethiopia, India, South Sudan, and Sudan. Kala-azar, also called visceral leishmaniasis, is a disease in which a parasite migrates to the internal organs such as the liver, spleen (hence "visceral"), and bone marrow. If left untreated, will almost always result in the death of the host. Cutaneous leishmaniasis is the most common form of leishmaniasis affecting humans. It is a skin infection caused by a single-celled parasite that is transmitted by the bite of a

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phlebotomine sandfly. There are about twenty species of *Leishmania* that may cause cutaneous leishmaniasis.

Keywords: Leishmaniasis, Neglected Tropical Disease, Human Health.

Introduction

Leishmaniasis is a neglected tropical disease infecting the world's poorest populations (Mann, 2021) It is a protozoan parasite, is a causative agent of disease leishmaniasis and it is second to malaria in terms of parasite-related mortality (Mathers et al., 2007; Mahajan et al., 2015). Every year an estimated 1.3 million new cases and 20 000 to 30 000 deaths are reported. About 90% of new cases occur in six countries: India, Bangladesh, Ethiopia, Brazil, South Sudan, and Sudan (WHO, 2014). The disease is diverse both in terms of diversity and complexity (Herwaldt, 1999). The disease is caused by more than 20 leishmanial species. The infection is spread to humans by ~30 different species of sandflies (Pearson and Sousa, 1996). Clinical symptoms include splenomegaly, hypergammaglobulinemia, prolonged fever and pancytopenia (Boelaert et al., 2000).

Clinical forms of disease

The disease manifests in four major clinical forms: visceral (Kala-azar), cutaneous (CL), mucocutaneous (Espundia) (MCL), and post-kala-azar dermal leishmaniasis (PKDL). Visceral leishmaniasis is considered the most dangerous form of the disease which targets bone marrow, liver, lymph nodes, and spleen (Roberts et al., 2000). Clinical symptoms of VL include hepatomegaly, splenomegaly, weight loss, hypergammaglobulinemia, and pancytopenia. (Stauch et al., 2011). Cutaneous leishmaniasis (CL) is the most common form, characterized by self-healing lesions; however, the healing process can involve months or years and varies with the infecting parasite species (Ameen, 2007). Mucocutaneous leishmaniasis (MCL) is caused most frequently by L. braziliensis. It is characterized by the destruction of the nasal septum or palate and occurs months or years after the cure of a primary CL lesion (David and Craft, 2009). Insect vector for the disease is female phlebotomine sandfly.

Morphology of parasite

There are two different morphological forms of *Leishmania* parasite: i.e. promastigotes (flagellate form) and amastigote (a flagellated form). Sandflies acquire the parasite, in the form of intracellular amastigotes from the vertebrate host and then transforms into extracellular promastigotes in the sandfly gut. In the midgut of the sandfly, the promastigotes develop into

infective and non-dividing metacyclic promastigotes. These are located near the stomadeal valve (an invagination of foregut into the midgut) in the anterior region of the fly's digestive canal. Once infective, the parasites invade their vector's mouthparts and then they can be transmitted to another vertebrate host when the fly attempts to take another blood meal (Killick-Kendrick, 1979). While taking a blood meal metacyclic promastigotes are regurgitated along with other immunomodulatory parasite-derived proteophosphoglycans and various salivary components. The metacyclic promastigotes are further rapidly phagocytosed by one of several possible cell types (neutrophils, tissue-resident macrophages or dendritic cell (DC) or monocyte-derived DCs (moDCs) present in that local environment. After the establishment of an intracellular environment, metacyclic promastigotes are transformed into nonmotile amastigotes which replicate within the host cells. When the host cells are packed with amastigotes, they rupture to release the same which again infect phagocytes. The transmission is complete when infected phagocytes are taken up by another sandfly with the blood meal and amastigotes then convert into promastigotes in the sandfly midgut (Killick-Kendrick, 1979).

Diagnosis

The definitive diagnosis of leishmaniasis is done by observing the parasite (amastigotes) on stained Giemsa smears or the culture of hepatic, splenic, or lymph node aspirates and bone marrow. The serological testing is useful with indirect fluorescent antibody test (IFAT), which is 80-100% sensitive in case of patients with visceral leishmaniasis who are not infected with HIV IFAT may show cross-reaction in patients who have schistosomiasis, malaria, leprosy, Chagas disease, tuberculosis and African trypanosomiasis (Singh et al., 2006). Further, ELISA can be combined with IFAT and/or western blot to increase its sensitivity (between 92% and 99%) and specificity (100%) (Singh et al., 2006). There are other serological diagnostic tests also which include latex agglutination, complement fixation test, indirect haemagglutination assay, direct agglutination test of amastigotes or promastigotes, counter-immunoelectrophoresis, FAST agglutination, whole parasite, and antigen-specific ELISA, rK-39 antigen dipstick assay, colloidal gold immunoassay, and western blotting (Reithinger et al., 2002)

Treatment

Current treatment of leishmaniasis relies on toxic drugs and relapse after cure remains a major problem. The lack of an effective vaccine against visceral leishmaniasis and growing limitations in available chemotherapeutic strategies further deepens the crisis (Bhaumik et al., 2009a). For many years, the pentavalent antimonials, meglumine antimoniate (Glucantime), and

sodium stibogluconate (Pentostam) have been used as first-line treatments against visceral and cutaneous forms of leishmaniasis. These drugs are no longer useful against Indian VL due to the development of resistance. Another effective drug against VL is amphotericin B deoxycholate (Fungizone) but is nephrotoxic, and its use requires 30 days of hospitalization (Olliaro and Sundar, 2009). A liposomal formulation of amphotericin B called AmBisome is also very effective against VL but is more expensive than the other current antileishmanial drugs (Olliaro and Sundar, 2009). Miltefosine is the first oral antileishmanial drug which was registered in India in 2002. Its limitations include teratogenicity, gastrointestinal tract toxicity, and is expensive (Olliaro and Sundar, 2009; Berman, 2006). Evaluation of the in vitro susceptibilities of Indian L. donovani patient isolates to sodium antimony gluconate, amphotericin B and miltefosine indicates that cross-resistance may be emerging among these three drugs (Kumar et al., 2009). AmBisome at a dose of 3.75-5 mg/kg followed by 7-14 days of treatment with miltefosine at a dose of 100 mg/day is highly effective against visceral leishmaniasis (cure rates 96-98%) (Sundar et al., 2008).

For a successful parasitic relationship with its host, evasion of both innate and adaptive immunity is a must for leishmanial parasites. The parasite invades the human body in its promastigote forms which are engulfed by macrophages but are resistant to proteolysis and degradation in phagosomes. In the mammalian host, *Leishmania* resides as amastigotes in phagocytic cells. The complement protein, C3b is one of the most potent immune opsonins which binds to the Leishmania parasite and results in uptake by the macrophage. Leishmania also possesses gp63 (a special surface glycoprotein), which is expressed more abundantly on the surface of metacyclic than procyclic promastigotes (Ramamoorthy et al., 1992; Kweider et al., 1989). This protein converts C3b to iC3b which in turn mediates the opsonic recognition of promastigotes by macrophage CR3 (Hermoso et al., 1991; Brittingham et al., 1995). In humans and experimental leishmaniasis, the immune response is usually mediated by T-lymphocytes which play an important role in generating specific and memory T-cell responses to intracellular parasitic infections and these have been widely distinguished in Leishmania infection. The Th-1 and Th-2 cells can be differentiated based on the cytokines they secrete: Th-1 cells secrete cytokines like IFN-γ and IL-12, while Th-2 cells secrete cytokines such as IL-4 and IL-10 which promote antibody responses (Scott, 1998). In leishmaniasis, cellular rather than humoral immune responses are involved in the recovery from disease. Spontaneous *Leishmania*-specific T cell response generally develops early after infection. The parasites first multiply as amastigotes in the phagolysosomes within the macrophages. Either intact

parasites or leishmanial antigens are then picked up by antigen-presenting cells (dendritic and Langerhans cells) that transfer them to CD4+ and CD8+ T cells (El-On, 2009). These cells activate specific T cells in the production of different cytokines and induce the macrophage to kill the intracellular parasites (El-On, 2009). Although several vaccine candidates have been tested in the past against leishmaniasis yet there is no effective vaccine against this parasitic disease. It has been documented recently that efforts to develop an effective *Leishmania* vaccine have been limited due to a lack of an appropriate adjuvant (Mutiso et al., 2010).

To date vaccine research against VL can be divided into three main groups: first-generation, second-generation, and third-generation vaccines. First-generation vaccines include vaccination with live virulent or killed parasites, second-generation vaccines include subunit vaccination with native/recombinant parasite proteins and third-generation vaccines include plasmid DNA and viral vector-based vaccines encoding parasite virulence factors. First-generation (killed) vaccines are relatively safe and they could be improved by the addition of suitable adjuvants to provide longer-lasting protection with fewer inoculations. Selection of a formulation for a given vaccine depends on the nature of the antigenic components, the preferred route of delivery, type of immune response desired, avoidance of considerable adverse effects, and stability of a vaccine (Mutiso et al., 2010). Several Leishmania proteins have been identified, based on abundance and surface localization (Handman et al., 1986). These include glycoprotein 63 (gp63), membrane glycoprotein 46 (gp46, also known as M-2), Leishmania homolog of receptors for activated C kinase (p36/LACK), cysteine proteinase CPB and CPA, LD1 antigens, hydrophilic acylated surface protein B1 (HASPB1), LCR1, salivary protein 15 (SP15), glycoprotein 46 (Gp-46/M-2), promastigote surface antigen 2 (PSA-2), histone H1, Leishmania elongation and initiation factor (Leif), L. major homolog of the eukaryotic stress-inducible protein-1 (LmSTI1), and the L. major homolog of the eukaryotic thiol-specific-antioxidant (TSA). However, identifying candidate antigens is not enough. Besides, a suitable antigen delivery to induce the right type of immune response (i.e. induction of a strong antigen-specific Th1 response) against leishmaniasis is another essential component of an effective vaccine. An effective vaccine could be integrated into a control strategy that would ideally comprise early and accurate diagnosis, effective and well-tolerated treatment, vector control, and personal protection from vectors (Desjeux, 2004). Leishmanization (LZ) is an ancient practice that involves inoculation using virulent parasites. It was traditionally practiced by transferring the infectious material from the cutaneous lesion to an uninfected individual. It was largely abandoned due to safety issues related to the use of live vaccines.

Leishmanization includes the management of cutaneous Leishmania parasites to a distinct membrane site and allowing a self-healing scratch to custom early immunological exposure that defends the patient from additional contagion and scratch growth. Apart from this, standardization of the inoculum proved difficult as parasites used for LZ experience a dramatic loss of infectivity after being repeatedly subcultured (Moddaber, 2010). The use of LZ is presently done only by Uzbekistan, wherever a grouping of living and deceased L. major is approved as a injection for high-risk people (Gafurov, 1999). As LZ is the only vaccine plan in contradiction of Leishmania with proven effectiveness in individuals so, hard work are being made to progress the protection outline of this rehearsal (Khamesipour et al., 2005). According to Brazilian scientists who worked as pioneers in research of first-generation vaccines, killed parasites were effective as both therapeutic and prophylactic vaccines (Noazin et al., 2008). Over the past 70 years, Brazilian investigators have been vaccinating against Leishmania using killed-organism preparations and have established the feasibility and safety of such an approach by injecting a five-strain combination of killed promastigotes (Antunes et al., 1986). Many arrangements of destroyed bugs unaccompanied then in amalgamation with various adjuvants have been tested to date. Despite the well-tolerated safety profile of the vaccines, no first-generation inoculation by dead parasites has established satisfactory effectiveness as a prophylactic preparation to date (Noazin et al., 2009). The first generation vaccines are modest and comparatively informal to producing Leishmania widespread nations at a little fee. However, it is difficult to standardize the inoculations resulting after refined bugs and this has vulnerable profitable progress efforts (Evans and Kedzierski, 2012). For the development of whole parasite vaccines, the important considerations to be taken into account include the vaccine formulation, the route of administration, and adjuvants. The growth of second-generation preparations for Leishmania contains recombinant proteins, poly-proteins, DNA inoculations, liposomal preparation, and dendritic cell inoculation transfer arrangements. Only a small number of recombinant proteins used against against VL in murine models. A promastigote-derived skin protein dp72 conferred protection in mice against L. donovani infection (Jaffe et al., 1990; Rachamim and Jaffe, 1993), but there has been no further advancing on the use of this antigen for the development of vaccines. The LCR1 protein of L. donovani amastigote was tested for protection in mice (Evans and Kedzierski, 2012). Amastigotes has shown effectiveness in an untried mouse model of VL (Stager et al., 2000). The protection induced by this vaccine was connected with the introduction of antigen-specific, "IFN-? producing CD8+ T cells, a mechanism similar to DNA vaccination" (Stager et al., 2000). A2 cysteine proteinase, another

protein of L. donovani when delivered as recombinant protein or as DNA afforded protection against experimental challenge infection (Ghosh et al., 2001a,b). Several other antigens have been tested. These include kinetoplastid membrane protein-11 (KMP-11), amastigote cysteine proteases (CP), amastigote LCR1, leishmanial antigen ORFF (Tewary et al., 2004a), and NH36, a major component of the fucose-mannose ligand (Aguilar-Be et al., 2005). In experimental infection systems against VL, multicomponent vaccines have been shown to impart protection apart from defined single molecules. Vaccination of dogs with a recombinant protein formed by the fusion of antigenic determinants from four cytoplasmic proteins of L. infantum along with living BCG conferred protection by enhancing parasite clearance (Molano et al., 2003). To date, Leish-111f is the only multicomponent vaccine that has been evaluated in clinical trials. It is composed of three molecules fused in tandem; the L. major stress-inducible protein-1 (LmSTI1), the L. major homolog of eukaryotic thiol-specific antioxidant (TSA), and the L. braziliensis elongation and initiation factor (Leif). Some studies from the past have also reported that the Leish-111f vaccine can also induce partial protection against VL in animal models (Coler et al., 2007), however, it failed to confer protection in dogs against infection. It was also unable to prevent disease development in a Phase III vaccine trial in dogs (Gradoni et al., 2005). An attuned version, identified as Leish-110f, has shown some protective efficacy and strong immunogenicity against L. infantum in mice (Bertholet et al., 2009). The Leish-111f vaccine is existence trialed in grouping with the MPL-SE adjuvant and is touching frontward into clinical trials as LeishF1. This adjuvant comprises monophosphoryl lipid A which is framed with the antigen as a stable blend. During a small scale clinical trial in an L. donovani endemic area, Leish-F1-MPL-SE was create to be acquitted and well-tolerated in people with and without prior VL exposure. The vaccine also induced strong antigen-specific T-cell immune responses (Chakravarty et al., 2011). Apart from recombinant proteins, DNA has also been widely tested as a means of vaccine delivery. The general property of DNA vaccines is the induction of Th1 type of immune responses leading to strong cytotoxic T cell-mediated immunity (Gurunathan et al., 2000). (Rodrigues et al., 2003). In hamsters immunized with PapLe22 antigen (which is recognized by T cells from VL patient) as a DNA vaccine, a significant decline in parasite load was observed (Fragaki et al., 2001). Artificial injection RAPSODI a DNA based LEISHDNAVAX (http://www.leishdnavax.org/) and an adenovirus vectored therapeutic vaccine are new European based VL vaccines (Modabber, 2010). Defensive injections are known as an excellent and most gainful defensive amount against pathogens and save millions of lives worldwide. The development of vaccines against leishmaniasis has proven to be a tough and challenging task

due to the complexity of immune responses needed for protection, inadequate knowledge of disease pathogenesis, and the cost of vaccine development (Evans and Kedzierski, 2012).

Gp46/M-2 is a GPI-anchored membrane protein that belongs to a family of genes expressed in most Leishmania species (McMahon-Pratt et al., 1992; Symons et al., 1994). Vaccination of mice with membrane glycoprotein gp46/M-2 has been demonstrated to provide significant protection in mice against challenge infection with L. amazonensis (Lohman et al., 1990; Champsi and McMahon-Pratt, 1988; McMahon-Pratt et al., 1993). In a murine model of VL, recombinant hydrophilic acylated surface protein B1 (rHASPB1), a member of a heterogeneous family of an acidic surface molecule, expressed only in metacyclic and amastigote stage of Leishmania life cycle is protective even in the absence of adjuvant (Stager et al., 2000). No the purified and vaccine efficacy of these antigens was revealed by 46%-49%, 65%- 67%, 72%-75%, and 74%- 77% reduction in parasite load respectively in BALB/c mice (Bhowmick and Ali, 2009). The 36kDa glycoprotein was identified as the major FML antigenic fraction, a surface glycoprotein antigen of *L. donovani*, and designated 'GP36' (Palatnik-de-Sousa et al., 1993). Immunization of BALB/c mice with GP36 along with saponin as an adjuvant by subcutaneous route induced. The specificity of the antigens and the skill of the adjuvant to generate an efficient protective immune response are the two major factors on which the efficacy of a particular vaccine formulation depends. For an immunosuppressor intracellular parasite like *L. donovani*, a good adjuvant should guarantee the maintenance of a strong humoral and cellular immune response against the pathogen. Immunization of hamsters and BALB/c mice with Saponins are considered to be the best adjuvants in several different experimental models (Scott et al., 1984; Britt et al., 1995; Khan et al., 1991). They are conjugates of glycoalkaloids or triterpenes and glycidic moieties and have been extensively used in vaccination of mice, canine and non-human primate experimental models. Immunization of isogenic CB hamster and BALB/c mice with the FML antigen in combination with Riedel De Haë¨n saponin via the intraperitoneal (i.p.) route, resulted in average protection of 87.7% and 84% respectively against visceral leishmaniasis (Santos et al., 1997). Strong immune response to the delivered antigen and long term protection against the infection are the two major roles of an effective adjuvant (Petrovsky and Aguilar, 2004). The term adjuvant is derived from the Latin word "adjuvant" which means to enhance or increase. The main problem with recombinant or synthetic antigens is that they are less immunogenic (McElarth, 1995; Marx et al., 1993; Douce et al., 1995). Hence, there is a strong need for powerful adjuvants to develop an effective antileishmanial vaccine. Besides increasing

the immunogenicity, adjuvants also reduce the amount of antigen dose or the number of immunizations to be given for protective immunity. The use of the right type of adjuvant is of central importance in vaccine formulations for a generation of an effective cell-mediated immune response against leishmaniasis.

Conclusion

As far as environmental impact on leishmaniasis is concerned various environmental factors increase the transmission risk, such as low socioeconomic levels, changes in land use and malnutrition. Additionally, climate parameters such as temperature, precipitation and humidity impact leishmaniasis transmission in multiple ways, whereas the temperature is the most significant factor. Leishmaniasis has been associated with climate change that rapidly leads to warmer conditions which attract sand flies towards temperate regions where habitat become warmer and therefore more suitable. Prediction of climatic suitability that increase transmission risk of vector-borne diseases is of crucial importance since efficient intervention can reduce disease transmission.

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CHAPTER-13

RENEWABLE ENERGY AND SUSTAINABLE TECHNOLOGIES

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Abstract

To combat the pressing environmental challenges like climate change and rising temperatures of the earth, minimizing the dependency on fossil fuels is the need of the hour. Deploying energy resources which are renewable, is one way to do this. The worldwide effects of pollution and the depletion of natural resources could be lessened by the effective use of renewable energy resources. This calls for a deep comprehension of the benefits of green technology and renewable energy. Renewable energy sources are thought to offer superior alternatives to conventional energy sources. Generally speaking, renewable energy comes from practically limitless sources, such as biomass, geothermal, hydro, wind, and solar energy, among others. The significance of renewable energy sources and its direct effects on the environment have been emphasised by sustainability scientists. Thus, focussing on green energy is essential to resolving the climate crisis and accomplishing sustainable development. Sustainable technology provides a means to redefine our engagement with contemporary developments to effectively tackle environmental and societal issues

Keywords: Renewable Energy, Sustainable, Environment.

Introduction

Climate change is already taking a toll on the planet earth. If the situation continues like this, its long-term negative implications will very certainly be substantial, costing far more than fighting it. In a recent report, IPCC conveyed Global Warming of 1.5°C and stressed that it is high time that we

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take real efforts to combat climate change, including alternate energy options. Considering that two thirds of greenhouse gas (GHG) emissions originate from the energy sector, the IPCC unequivocally calls for an immediate, large-scale shift to renewable energy and energy efficiency (Dicko et al., 2025).

Energy is necessary for all human activities, including transportation, cooking, lighting, and supporting productive processes. However, as a result of all human activity, the climate has been changing at an alarming rate in recent years. The average temperature of the Earth has increased during the last century, according to most scientists. Sea levels will rise as a result of this trend, and scientists warn that more frequent floods, heat waves, droughts, and other extreme weather events might result in the extinction of wildlife and habitats. Generally speaking, the best solutions we can use to mitigate the worst effects of global warming are sustainability and renewable energy. Energy services must be delivered in an environmentally friendly manner with low greenhouse gas emissions for development to be sustainable. Renewable energy source is the answer to these requirements.

Renewable Energy Resources

For the past one and half century, humans have primarily depended upon fossil fuels to run their homes, factories and vehicles and almost every activity. It's easy to use traditional fuels like coal and natural gas for our energy requirements. About 74% of the India's energy demand is still met by coal and oil. But we should be aware that we have a restricted supply of these fuels with us. We are using them at much faster rate than they are being generated. Eventually, they will expire. Also, pollutants emitted by these fuels take a significant toll on the environment—and of course on humans. Air pollution results in many kinds of respiratory diseases. Acid rain caused by sulphur dioxide and nitrogen oxides harms plants and marine animals. Nitrogen oxide can lead to smog. Additionally, burning fossil fuels emits greenhouse gases into the atmosphere, trapping the sun's heat and causing global warming. Renewable energy sources hold the key to these problems. We often call renewable energy technologies "clean" or "green" because they produce few if any pollutants.

In the COP26, Climate Change Conference, organised in 2021 in Glasgow (on the recommendations of the UN) representatives of the 197 nations made a contract towards limiting reliance on coal and other conventional fuels. Furthermore, the conference stated 'the various opportunities for governments to prioritize health and equity in the international climate movement and sustainable development agenda'. Also, one of the testaments is the necessity to 'create energy systems that protect and improve climate and health' (WHO, 2021; Hunter et al., 2021). Today, Govt. is providing

various financial helps to make it easier for organisations to rely on renewable resources as a continuous source of energy to help stave off the climate change. However, in order to assist the world, reach the goal of net-zero emissions, the forthcoming generation of clean energy needs more than simply encouragements; it also needs cutting-edge technology to increase Electricity production and energy optimisation

To ensure sustainable development, numerous nations have begun to invest in these renewable energy sources. About 286 billion dollars were invested in 2015, with hydroelectricity, solar power, wind, and biofuel being the main industries. Production and trading companies require a green blueprint. These initiatives aim to improve the environmental impact of human activity while minimising carbon footprints and emissions.

Renewable energy is generated from natural resources that are replenished more rapidly than they are utilised. Wind, hydroelectric, and solar power are typical examples. Transportation, the rural sector, electricity generation, and air and water cooling and heating are some of the uses for the energy supplied by renewable energy resources.

Types of Renewable Energy Resources

Solar Energy

Solar energy means to make use of the light and heat of sun as a form of energy which can be employed using various technologies such as solar electricity, solar thermal energy (including solar water heating) and solar architecture (Maka & Alabid, 2022). It is a significant source of renewable energy of uses. In 2011, the International Energy Agency said that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible, and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating global warming these advantages are global" (Timilsina et al., 2011; Marques et al., 2022).

Approximately half of incoming solar energy reaches the Earth's surface. The Earth receives 174 petawatts (PW) of incoming solar radiation at the upper atmosphere (Smil, 1991). About 30% of it is reflected back, with the rest 122 PW being absorbed by land, water, and clouds. Humans' potential solar energy differs from the quantity of solar energy present near the planet's surface because factors such as geography, temporal variation, cloud cover, and available land limit the amount of solar energy that can be used. The World Energy Council, UN Department of Economic and Social Affairs, and

United Nations Development Programme (UNEP) in 2000, collectively released an assessment of the annual amount of solar energy that humans could use, accounting for insolation, cloud cover, and the amount of land that is suitable for human use.

1 Solar Electricity

Solar power technologies are named as passive solar or active solar according to the way they collect and provide solar energy or change it into solar power. Solar power also known as solar electricity is transforming sunlight to electrical energy and it can occur in two ways, solar photovoltaics (PV) or concentrating solar-thermal power (CSP). The easiest method, solar PV, gathers sunlight using solar panels, alters it to electrical energy and stores it in batteries for numerous uses. Active solar technologies increase the supply of energy and are considered supply side technologies, while passive solar technologies reduce the need for alternative resources and are generally considered demand-side technologies (Philibert, 2005).

Photovoltaics (PV) were only employed for drawing electric power in the beginning, for applications of small and medium order, from a modest calculator using power of a single solar cell to normal homes powered by a PV system installed on a roof. Commercial concentrated solar power plants were first developed in the 1980s. Due to decreasing material prices and advancements in installation processes, the cost of solar power has dropped almost 90% over the past decade, making it more accessible and cost-effective (Brown, 2015). Due to global shifts in the electric industry's structure and advancements in solar technology, a robust solar electric market has developed over the past ten years for powering homes and buildings that are connected to a grid, in big cities. Solar electricity is frequently a cost-effective substitute for energy-saving devices in isolated locations.

2 Solar Thermal Electricity

Solar thermal electric systems use the heat from the sun to generate energy, as opposed to solar-electric systems that use sunlight. Concentrating solar power (CSP) methods employ mirrors to direct sunlight onto a receiver, which is a component that generates electricity. This technology is mainly utilised in large-scale power facilities that supply electricity to towns and communities.

3 Thermal energy

Solar thermal technologies can be used for water heating, space heating, space cooling and process heat generation (Mostafaeipour et al., 2021). Solar hot water systems use sunlight to heat water. Part of this energy can be countered by solar heating, cooling, and ventilation systems. Depending on

whether active components like sun tracking and solar concentrator optics are utilised, solar heating applications can be broadly classified as either passive or active.

Utilising deciduous plants and trees to capture solar heat has been common. When planted on the southern side of a building in the northern hemisphere or the northern side in the southern hemisphere, their leaves provide shade during the summer and make light to pass during the winter season (Mazria, 1979).

4 Water treatment

Solar distillation can be used to make saline water usable. Solar heat is mentioned to be first used for this purpose by 16th-century Arab alchemists (Das et al., 2020). A large-scale solar distillation project was first set up in 1872 in the Chilean mining town of Las Salinas (Silva et al., 2023). Solar water disinfection (SODIS) has been advised by WHO as practical method for desalination of household water (Chauque &Rott, 2021). It consists of exposing water-filled plastic polyethylene terephthalate (PET) bottles to sunlight for several hours (Meierhofer & Wegelin, 2002). Duration of contact of water containers with sunlight is contingent upon weather conditions, ranging from a minimum of six hours to a maximum of two days during completely cloudy conditions. In poor nations, more than two million individuals get their drinking water from this way every day. Water in a pond can be treated using solar energy instead of chemicals or power.

5. Household Chores

Solar cookers are simplest appliance based on solar power. They use sunlight for cooking and reheating. They can be classified into three categories: box cookers, panel cookers, and reflector cookers. The simplest solar cooker is the box cooker first built by Horace de Saussure in 1767 (Halacy &Halacy, 1992). An insulated container with a clear lid makes up a simple box cooker. For commercial and industrial purposes, solar concentrating systems like Scheffler reflectors, troughs, and parabolic dishes can supply process heat. Clothes racks use neither gas nor electricity to dry clothes by allowing them to evaporate in the sun and wind. Unglazed transpired collectors (UTC) can produce 45–60°F outlet temperatures and increase the temperature of the entering air to up to 22°C (40°F). More than 80 systems, totalling 35,000 square meters (380,000 square feet) of collector area, had been installed globally as of 2003. One such unit is in Coimbatore, India spread over a1,300 m2 (14,000 sq ft) collector area, employed for drying marigolds.

Wind energy

Wind energy uses naturally flowing air in the Earth's atmosphere to generate mechanical power and electricity. From ancient times, windmills have been utilized by humans to capture the untamed energy of wind. It is cheapest and completely renewable resource and has least environmental impacts. Like solar, wind is irregular and depends on site, which can pose hurdles for transmission and grid integration. Since 1990, it has become the world's fastest-growing energy source thanks to technological advancements and design improvements, growing at an average annual pace of more than 25%. Onshore or offshore, it has tremendous potential.

These days, wind turbines—which work differently than windmills—are a far more efficient technology that transforms that energy into power when paired with sophisticated generators. From small-scale windmills for residential use to large-scale wind farms, wind turbines have advanced in size. To potentially double offshore wind power output, large-scale wind farms are being planned to capture stronger offshore winds. Wind energy can help lower energy costs, support clean energy jobs and further reduce the country’s reliance on fossil fuels (Kataray et al., 2023).

Forecasting renewable energy production is essential to ensuring a steady, sustainable, and affordable electric supply. Renewables forecasting is a solution built on AI, sensors, machine learning, geospatial data, advanced analytics, best-in-class weather data and more to generate accurate, consistent forecasts for variable renewable energy resources like wind (Melikoglu, 2017).

Hydropower

Approximately 10% of the country's electricity is generated by hydropower, one of the biggest and oldest renewable energy sources. There are now roughly 77,000 megawatts (MW) of hydropower available. Electricity is produced by hydropower facilities using the energy of flowing water. A dam on a river is used in the most popular type of hydropower to hold a sizable reservoir of water. Turbines are turned by water to produce power. Although hydropower plants don't pollute the air, they can have an impact on wildlife habitats and water quality. As a result, hydropower facilities are currently being planned to have as little of an impact as possible on water bodies. In order to replicate the river's natural flow, a portion of the flow is occasionally redirected. However, this lowers the power plant's output even while it enhances the habitat for wildlife.

A sustainable energy source with little effect on nearby ecosystems, small-scale hydro unit uses a pump, turbine, or waterwheel to transform the natural flow of water bodies into power. Compared to most other sources, hydropower is a reasonably priced source of electricity. With innovative new technologies emerging, the IEA predicts that hydro will continue to be the greatest source of clean energy through 2030 [Kataray et al., 2023; Amold et al., 2023]. After that, it will keep playing a vital part in enhancing system flexibility and decarbonising the electricity system. Because hydropower is a site-specific technology, these expenses can be reduced with careful planning, including site and design choices.

Three turbines constructed of a novel thermoplastic composite material—which is more recyclable and less prone to corrosion than conventional materials—were installed in the East River of New York City in 2021 by the National Renewable Energy Laboratory (NREL). Although there was no visible structural damage, the new turbines produced the same amount of electricity in the same amount of time as their predecessors.7. Although testing under extreme conditions is still required, if widely used, this inexpensive, recyclable material has the potential to completely transform the hydropower industry (Koike & Tomita, 2023).

Geothermal Energy

The heat generated by the decay of radioactive elements in the Earth's crust and transmitted to the subsurface by conduction and convection is known as geothermal energy. Using steam or hydrocarbons, geothermal power plants and small-scale geothermal heat pumps (GHPs) transform heat from the Earth's interior into electrical power. In the past, access to geothermal reservoirs located deep beneath the Earth's crust was necessary for geothermal energy to function. Geothermal location independence is being researched.

In regions of the world where geothermal energy production was previously impractical, enhanced geothermal systems (EGS) provide the required water from beneath the surface of the Earth. Additionally, as ESG technology advances, harnessing the Earth's boundless heat reserves could yield an endless supply of affordable, clean energy for everyone.

Geothermal power plants come in three varieties: binary cycle, flash steam, and dry steam (Griffiths et al., 2024). While binary cycle and flash steam plants draw from hot water reservoirs, dry steam plants draw from steam reservoirs. Binary-cycle plants move heat from the water to a working fluid, which is different from both steam and flash plants. Instead of burning fuels, GHPs transmit heat between dwellings and the land, which makes them

incredibly efficient and clean. In actuality, even the most energy-efficient furnaces available today are at least three times less efficient than GHPs.

Biomass

Biomass, which consists of organic material such as plants and algae is used to create bioenergy. Numerous sectors, including those engaged in building and agricultural product processing, can produce significant amounts of leftover biomass, which can be used as a source of bioenergy. Even though biomass is frequently contested as being genuinely renewable, modern bioenergy produces almost no emissions. With more than 7,000 MW of installed capacity, biomass is the second-largest renewable energy source in this nation after hydropower.

Particularly intriguing are research developments in biofuels, such as bioethanol and biodiesel. Australian scientists are studying transforming organic materials into sustainable aircraft fuels (SAF). This could help reduce jet fuel carbon emissions by up to 80% (Oro et al., 2015) Stateside, the US Department of Energy's (DOE) Bioenergy Technologies Office (BETO) is developing technology to help reduce the costs and environmental impacts of bioenergy and bioproduct production (Ptal & Lis, 2025). Certain enterprises have noticed that switching to biomass in place of certain coal is a low-cost method of lowering unwanted emissions. It is possible to replace up to 15% of the coal with biomass. Because biomass produces less nitrous oxide and sulphur dioxide, acid rain is less likely to occur. Using a process known as gasification, biomass is transformed into gas that is then burned in a gas turbine to produce power. Gas, primarily methane, is also produced by the decomposition of biomass in landfills and can be utilised in industry or to generate steam for the production of electricity. It is also possible to heat biomass without oxygen to chemically transform it into pyrolysis oil, a kind of fuel oil that can be utilised as a feedstock for fuel and chemical production as well as for power generation. Biofuels are liquid fuels that can be made directly from biomass. Biofuels are chosen over other fuels for automobiles due to their high energy density and ease of transportation. Ethanol, an alcohol produced by fermenting biomass that contains a lot of carbs, is the most widely used biofuel. To help fulfil air quality regulations, it can be added to petrol. Biodiesel, which may be produced from both vegetable and animal fats, is another type of biofuel. Because of its easy access to land, ideal agricultural climate, and inexpensive labour, India has an edge in the production of bioenergy

Sustainable Technology

Sustainability means exercises that are viable feasible in the long run because they do not cause environmental damage (Mittal & Bansal, 2024). It is the most discussed term to lower carbon footprint. Sustainable technology is an umbrella term with two main ideas, both of which include innovations that foster social, economic, and environmental prosperity (Fowdur et al., 2022). The technology that aids in reducing an existing environmental issue comes first. For instance, renewable energy technology reduces carbon emissions and the need to burn fossil fuels by producing electricity from solar and wind power. The technology that directly solves an environmental problem comes in second. For instance, carbon emissions from the atmosphere are captured and stored via carbon capture technology. Carbon capture has the potential to cut global greenhouse gas emissions by 14% by 2050. People are encouraged by technology to make more environmentally, economically, and politically responsible decisions. The use of digital technology might reduce emissions worldwide by 17%.

For sustainability, technology is crucial for the following reasons.
(a) Burning fossil fuels for energy causes the globe to overheat due to greenhouse gas emissions, which in turn causes adverse weather patterns, increasing sea levels, food shortages, and other issues.
Solution: We can lessen our reliance on fossil fuels and lower our carbon footprint by converting to sustainable technology that maximises renewable energy.
(b) Loss of Biodiversity: The biggest problems brought on by climate change are habitat loss, ecological destruction, and even the extinction of entire species.
Solution: People are encouraged by technology to make more environmentally and socially responsible decisions. For instance, sustainable clothing and vertical farming.

Examples of Sustainable Technology

Electronic Industry: To prevent e-waste, smartphones with detachable batteries are used. For the construction of sustainable technologies like solar panels, wind turbines, and electric vehicle batteries, minerals like graphite, lithium, and cobalt are required.

In agriculture, vertical farming and sustainable technologies are used to track crop health and water level in order to maximise water use and boost productivity. Additionally, drones can be used to sprinkle fertiliser and monitor crop health using cameras. To cut down on the quantity of area required for agriculture, vertical farming entails stacking and building up rows of crops vertically (Source: Eden Green). For this farming technique to

be successful, artificial temperature, light, and humidity control are needed. AI and IoT technologies are used in vertical farming to automate crop monitoring and growth.

There are more familiar sustainability technologies like solar panels.



Fig 1. Solar panels -most common example of sustainable technology

Telepathy and computerised medical reports are utilised in the healthcare industry to eliminate the requirement for paper documentation while also making the data easier to process.

Virtual try-on services can significantly cut waste and returns in the apparel sector. Additionally, using sustainable and biodegradable fabric to produce clothing is popular.

In smart cities, street lighting is equipped with sustainable technology and LED lighting, also known as solid state lighting (SSL), which uses a lot less energy. There are plans to build net-zero buildings with rainwater harvesting systems.

Electric automobiles are replacing combustion-engine vehicles. This calls for the construction of EV charging infrastructure in addition to a rise in the use of buses and other electrified public transportation vehicles.

Sustainable Technology- Benefits and Challenges

The reduction of detrimental environmental effects is the clear advantage of sustainable technology. However, in certain situations, this can also result in decreased water use, cheaper expenses, and improved efficiency. Additionally, sustainable technology can improve the quality of settings. That can have a special effect on homes, workplaces, and even important tourist locations like cities. Sustainable technology not only supports environmental preservation but also boosts economics. The climate catastrophe presents a chance to strengthen economies through job creation and increased business opportunities in the sustainable technology sector. Startups have the

opportunity to expand as a result of the demand for sustainable digital innovation, which also generates new jobs and possibilities. Additionally, there is a fantastic chance to draw in and develop talent among young minds.

Increased use of Internet of Things (IoT) sensors and gadgets, which are perfect for maximising efficiency in many domains, is a common component of sustainable technology. However, these also provide security issues. A system is somewhat vulnerable to hacking or compromise once it is connected to the internet. This technology has its own energy footprint as well, so a realistic approach is necessary to make sure the overall advantages live up to the hype. Similar to this, e-waste can be a problem for sustainable technology, especially if it uses gadgets with short lifespans.

Scope of Improvement

There is a continuing need for new technology in a world that is more digitally connected than ever before, which calls for networks, data centres, and applications. One drawback is the substantial carbon footprint that digital technology itself leaves behind, despite the fact that it is the key to becoming more sustainable across industries.Currently, the majority of major service providers are working to lessen the effects. Companies like Google and Facebook use newer servers and better cooling systems as solutions to this issue (Source: Forbes). Google uses artificial intelligence (AI) to control its cooling systems by tracking and responding to operational and meteorological circumstances automatically. Facebook make use of Autoscale technology to limit the number of servers that must be up and running during periods of low demand, resulting in a 10% to 15% reduction in energy use. (Source: Knowledge of Data Centres).

One of the best strategies to reduce these environmental hazards is to properly recycle electronics to keep e-waste out of landfills. In addition to recycling, buying products that have an eco-friendly label and giving or fixing old gadgets are two further strategies to cut down on e-waste.



Recycling E-Waste	Food Waste Apps	Smart mobility	Blockchain	Cloud Sustainability

Fig 2. Current Sustainability Trends

Conclusion

To maintain temperatures below 1.5°C and 2°C, researchers calculate how much more CO2 we can emit. This is referred to as the global "carbon budget. Over 2024-2030, global cumulative heat related emissions are expected to exceed 100 Gt CO2, almost 30% of the carbon budget for a 50% likelihood of limiting global warming to 1.5°C. Switching to renewable energy resources is one step towards reducing carbon footprints. During 2024–2030, the world's use of renewable sources is predicted to climb by almost 50%, or over 2.4 times the previous six-year growth.

Ironically, we must rely on technology to lessen the adverse effects on the environment, even though humans' departure from their natural lifestyles is thought to be a major contributing factor. Creating and implementing sustainable technology is an investment in a more environmentally friendly future. We can undo the negative effects of human activity on the environment thanks to sustainable technology. Adopting cutting-edge sustainable technology helps people deal with complicated climate concerns like massive energy use, greenhouse gas emissions, and e-waste. Businesses, industries, and governments should continue to place a high premium on adopting these technologies. It is possible to combat the climate catastrophe, but everyone must contribute to creating a more sustainable environment. Investing in sustainable technology entails investing in economic growth, innovation, and startup potential.

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CHAPTER-14

BIOFUELS FOR SUSTAINABLE FUTURE

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Abstract

The contemporary era is facing exceptionally huge predicament due to the skyrocketing demands of energy at global level and emission of carbon dioxide, owing to the exhaustion of fossil fuels. This intercontinental concern regarding energy preservation and environmental conservation has allured researchers to hunt for alternative sources of energy, especially for the transport sector. Fossil fuels are the conventional fuels that constitute the main sources of non-renewable energy that are not sustainable in case they are lost. There has been a significant increase in the rate of carbon dioxide emission and the energy consumption globally. These upsurge rates are a driving force to mankind and the environment. However, the renewable sources like biofuel showcase a promising alternative with less emission of carbon dioxide, less pollution and can be produced from organic waste. Moreover, they are efficacious against emission of greenhouse gases (GHGs) and have little repercussions on the climate change resulting from transportation vehicles. The research on biofuels is at global level because of the two chief properties, renewability and sustainability. The production of biomass fall into three categories, namely, the First generation, Second generation and Third generation biofuel. The first generation comprises food crop-related biomass,

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whereas the second generation includes lingo-cellulosic biomass, and the third generation features algal biomass.

Keywords: Environmental protection; Fossil fuels; Non-renewable energy; Renewability; Sustainability

Introduction

Biofuels are the fuels that are produced from biomass. They may be solid (Wood, dried plant material, and manure), liquid (Bioethanol and Biodiesel) or gaseous (Biogas) in nature (Demirbas et. al., 2016) Today, ethanol can be produced from maize, molasses, sugar cane, wheat, and some other grains like cassava or sugar beets. Similarly, biodiesel is based on vegetable oils (soybean oil, or rapeseed oil) or waste cooking oils. They can be produced in a short period of time; days, weeks, or even months. The biofuel sectors at international level are significantly influenced by three main objectives viz. support from farmers, reduction in emission of greenhouse gas, and deduced energy independency.

The transport sector has a paramount contribution in a country's socioeconomic growth and development and transportation services are affordably and safely provided by governments. More than 90% of the fossil fuel products are consumed in the transportation sector (Subramanian, 2017). Almost a quarter of energy is consumed by transport sector for running multifarious land, air and water vehicles such as cars and bikes, buses, airplanes, trains, trucks, and ships. It is estimated that in the upcoming decade, the liquid biofuel consumption will increase substantially. Running the vehicles on fossil fuels will lead to unimaginable environmental consequences (global warming and increasing air pollution) and costs. Thus, the Low-carbon transport systems include biofuels, hydrogen, and electric vehicles (EVs) will become inevitable (Lamb & Austbo, 2020). They will have certain advantageous properties that can minimize the pollutants and CO_2 emissions from Internal Combustion engines.

Types of Biofuels

1. **Bioethanol:** It is obtained from crops such as sugarcane and corn via process of fermentation and constitutes about two-thirds of the energy provided by petrol per liter. When mixed with petrol, it enhances combustion efficiency and reduces emissions of carbon monoxide and sulfur oxide (Erbaum, 2009).
2. **Biogas:** It is produced by the anaerobic decomposition of organic matter such as human sewage and animal

waste that is predominantly composed of methane and carbon dioxide, with minute quantities of hydrogen, hydrogen sulfide, and carbon monoxide. It is generally utilized for heating, electricity generation, and as fuel for automobiles.

3. **Biodiesel:** The biodiesel can be produced from vegetable oils like palm oil and soybean, animal fats and waste vegetable oils through "Trans-esterification" (Barnwal & Sharma, 2005). It produces minimal or no harmful gases than the conventional diesel. It can be a substitute for traditional diesel.
4. **Biobutanol**: Biobutanol can be produced by the starch fermentation and releases the maximum energy among other gasoline alternatives. Moreover, it can be blended with diesel to alleviate emissions. Also, it acts as a solvent in the textile industry and cosmetics.
5. **Biohydrogen**: Various processes such as pyrolysis, gasification, or biological fermentation can be employed for producing biohydrogen and it offers a prominent alternative to fossil fuels.

Various Generations of Biofuels (Fig 1)

First Generation Biofuels:

Bioethanol, Bioethers, Biogas and Biodiesel are the first generation biofuels produced through microbial fermentation of sucrose and starch rich edible feedstocks such as wheat, maize, and sugarcane (Jacobus et al., 2021). Some commercial strains of microbes are *Saccharomyces cerevisiae*, and *Saccharomyces stipites*. Bioethanol can also be categorized as second and third generation on the basis of the feedstock and production strain (Favaro et al., 2019; Jacobus et al., 2021; Mohammad et al., 2017; Subramanian, 2017). Mainly, they are produced using conventional technology from food-based biomass such as corn, wheat, soy and sugarcane having sugar, starch, vegetable oil, or animal fats as the food sources. The sugars, oils or animal fats present in the biomass can be converted into liquid fuels by fermentation or chemical processes involved in their production. In contrast to bioethanol, the production of biodiesel include certain steps that are catalyzed by chemicals, such as lipid trans-esterification with alcohols. However, the enzymatic catalysis is currently being employed for laboratory production (Arthy et al., 2014; Fattah et al., 2020). Apart from this, the production of biobutanol is also possible by sugar fermentation from a variety of crops, but

it is restricted due to its lower productivity, product inhibition, and high costs (Jiang et al., 2019; Karthik &Nanthagopal, 2021; Sindhu et al., 2019; Vamsi et al., 2022).

A



B

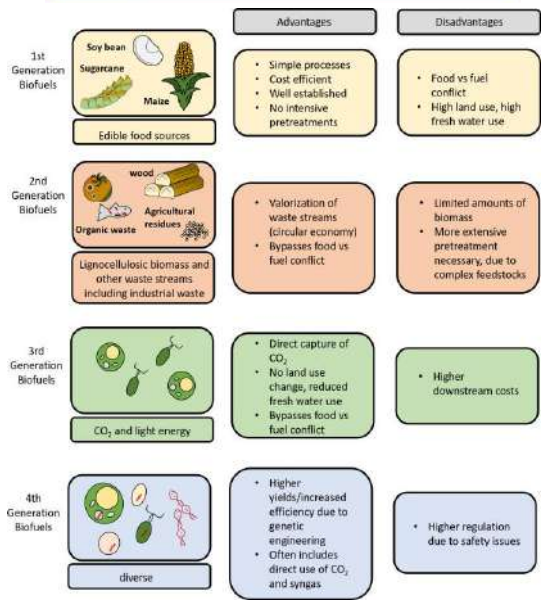


Fig.1(A) Different generations of biofuels and (B) Advantages and disadvantages of various types of biofuels

Second Generation Biofuels:

The development of second-generation biofuels resulted due to the issues of the first generation biofuels, and focused on utilizing lingo-cellulosic biomass from agricultural and woodland residues as well as other waste streams (wheat bran, animal fats, or wastes of cooking and frying oil) (Arthy et al., 2014; Fattah et al., 2020). Second-generation biofuels are prepared from perennial grasses and quick-growing trees or from the non-eatable parts of food crops, incuding, husks, wood chips, stems, and fruit skins. Another non-food plants like *Jatropha curcas* can also be a promising source for second-generation biofuels (Kumar & Sharma, 2008). Thus, the second-generation biofuels bypass the requirement for change of agricultural land use and not at all compete with food resources. The processes to make second-generation biofuels are bit complicated in terms of more processing time and costs (Joshi et al., 2017; Malode et al., 2021; Mischko et al., 2018) and involves converting cellulose into fuel. They are generated through thermo-chemical reactions or biochemical conversion processes.

Examples: cellulose, ethanol and biodiesel.

Third Generation Biofuels:

These are mainly derived from the biomass of microalgae and cyanobacteria that can be utilized to generate lipids and alcohols that can further be transformed into biodiesel or any other high energy fuel. Algae produces faster biomass formation owing to their higher photosynthesis rates than terrestrial plants (Li et al., 2008). Another noteworthy point is that the algae do not require fresh water for cultivation, rather they can be grown using waste water, or salt water, that is cost efficient and do not impose any threat to agricultural activities (Borowitzka & Moheimani, 2010; Melcher et al., 2021). Moreover, industrial sources and atmospheric carbon can be captured to supply direct CO_2 for efficient algae cultivation. As per the conventional cultivation systems, approximately 75% of supplied CO_2 is used for photosynthesis and therefore biomass production (Doucha & Livansky, 2006). Hence, algal biofuels actually lead to a negative carbon footprint because they directly bind to greenhouse gases in their biomass.

Example: Butanol, Biokerosene

***Algal bioreactors** (Fig 2): Algae can be commonly cultivated in open ponds, also termed as Algal bioreactors that can be effectively utilized for low price and high volume biofuels being independent of climate and location. However, these open pond reactors may lead to high water loss through evaporation or there may be lack of temperature control that can ultimately lower the biomass productivity. In such cases, the closed photo-bioreactors

are used in which processing parameters can be precisely controlled to obtain high price, low volume products with a higher productivity (Melcher et al., 2021; Neto et al., 2019)



Fig. 2 Algal bioreactor

Fourth Generation Biofuels:

The fourth-generation biofuels use recombinant DNA technology to improvise the desired characteristics of organisms that are employed in biofuel production. Some of the desired traits include utilization of multiple types of sugars (pentoses and hexoses), high lipid synthesis, increased rate of photosynthesis and carbon fixation (Abdullah et al., 2019; Sharma et al., 2019). Presently, two approaches are being adopted, the first involving genetic engineering of pathways in indigenous producers (optimizing growth rates, utilization of different carbon sources, directing the metabolic flux toward biofuel production) and the second focusing on reconstruction of pathways identified in natural producers in more genetically accessible model organisms. A wide array of microbes can be used as hosts for biofuel production, including bacteria, yeast, and algae. They are metabolically versatile that enables the use of varied types of substrates to produce different biofuels.

Conversion Pathways for the Production of Varied Types of Biofuels

The thermochemical process is more suitable for dry biomass with lower moisture as they are characterized by having higher temperature and high conversion rates. On the other hand, biochemical processes are quite suitable for wet biomass that is rich in organic matter (Slade & Bauen, 2013).

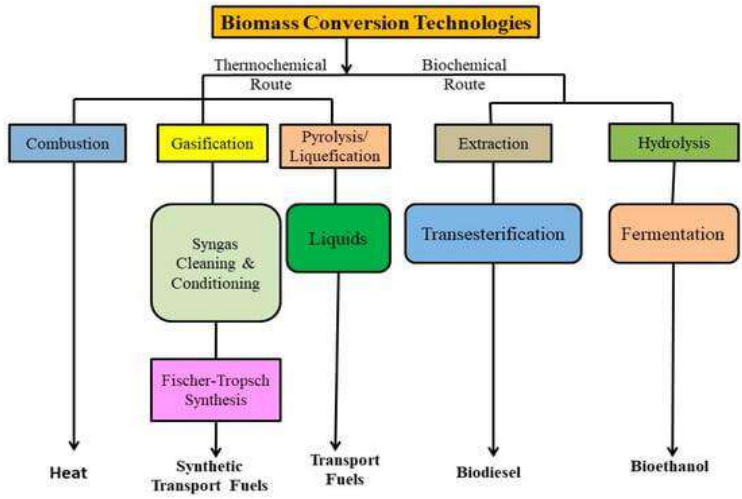


Figure 3 (A). Biomass conversion technology for biofuels production.

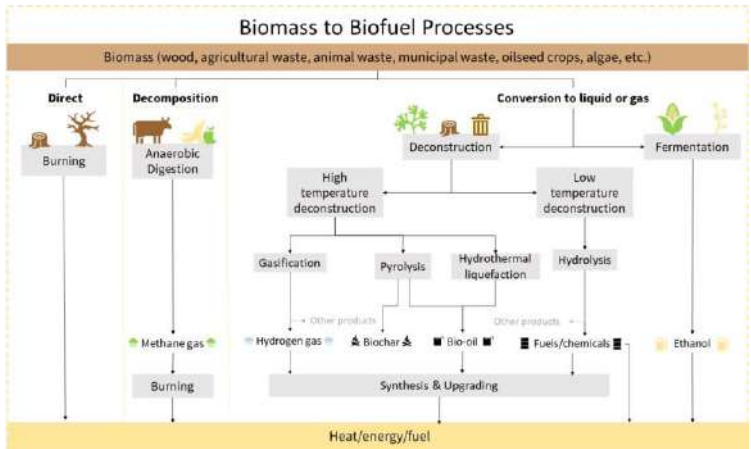


Fig 3 (B). Biomass conversion technology for biofuels production

for wet biomass that is rich in organic matter (Slade & Bauen, 2013). Biofuels (bioethanol and biogas) derived from renewable sources like agricultural residues, planting materials, starch and sugars crops, and wood via liquefaction, saccharification, enzymatic hydrolysis, fermentation, and anaerobic digestion conversion technologies. Likewise, biodiesel is derived from biomass of plant oils, animal fats, and algae through trans-esterification

and dark fermentation process (Araujo et al., 2018). Conventionally, the method of transesterification is employed to convert the oils and fats derived from oilseed crops into biodeiesel and this process involve certain chemical reactions with methanol or other alcohols. However, the woody biomass as well as agricultural residues (lignocellulosic feedstocks) demand treatment with acids to dissociate hemicelluloses and cellulose into sugars, those, with the help of microbial agents, can be reformed into hydrocarbons. The commercial production of biofuels can be accomplished via pyrolysis or liquefaction (Thermochemical conversion processes). During pyrolysis, the organic matter get decomposed thermo-chemically at 400–600 °C in absence of oxygen and results in the production of oxygenated bio-oil and biochar along with non-condensable gases.. Another promising thermo-chemical method is gasification, wherein biomass is transformed into syngas which is a mixture of H_2, CO, CH_4, CO_2 and N_2 by heating the substrates at high temperatures (>700 °C) and reacting with air, oxygen or steam. The resultant syngas can be converted into liquid fuels by renowned reactions like Fischer-Tropsch synthesis. Recently, microalgae has emerged as a breakthrough feedstock for preparing liquid transportation fuel because of its characteristic potential to use carbon dioxide from industrial activities, high efficiency for photosynthesis, and ability to be grown on marginal areas. The biofuels derived from algae do not directly affect food crops, unlike those derived from soybean, corn, or sugarcane.

Advantages and Disadvantages of Biofuels.

Advantages:

Biofuels are considered to be a form of renewable energy, being derived from plants and the primary crops used in their production can be grown ubiquitously and repeatedly (Datta et al., 2019). Thus, owing to their abundant supply, they will not become scarce. Secondly, unlike the fossil fuels, their production and delivery is highly efficient. As far as energy efficiencies are concerned, the clean burning of biofuels results in lesser deposits. Additionally, they render increased lubricity that help in preventing friction-based engine wear. Another noteworthy merit is the cost-effectiveness of biofuels as compared to the conventional fossil fuels (Datta et al., 2019). One more primary advantage of biofuels is that their use in current gasoline and diesel engine vehicles does not require any adaptations, or replacements. Apart from this, biofuels outshines the fossil fuels in terms of GHG emissions. The GHG reductions achieved by biofuels present their most significant advantage over fossil fuels (Finco, 2012). Last, but not the least, adoption of biofuels will intrinsically plunge the pollution levels, especially

for airborne particles such as nitrous oxide (NO) emitted by diesel. Pure biodiesel and ethanol are both biodegradable without any ill-effects. Thus, even little blending with fossil fuels can result in pollution deductions.

Disadvantages:

Every new technology comes with its own share of pros and cons, so are the biofuels. This industry demands subsidies from government in order to remain price-competitive with fossil fuels owing to their extremely high production costs. Secondly, although biofuels emit fewer GHGs and other pollutants when consumed, achieving greater agricultural production requires more water and fertilizer (Datta et al., 2019). Water-intensive biofuel crops may have adverse local and global impacts. The excessive use of fertilizers upsurges the level of nitrogen, phosphorus, and other chemical in the environments that become severely lethal, particularly when soil is carried by water runoffs as it may enter drinking sources or new ecosystems. Not only this, when biofuel and culinary sector would compete for the similar resources, rates will hike while obtainability will plunge. However, it is noteworthy that later generations of biofuels targeting sources that will not compete with food supplies (e.g., algae). It is observed that farm establishments for producing raw material for biofuels requires land-clearance that in turn can damage the global ecosystems. As an illustration, it's estimated that nearly 11 million hectares of tropical forests and peat will be damaged to meet palm and soy oil demand alone (Datta et al., 2019). Moreover, Biofuels are intrinsically have higher sensitivity to low temperatures than fossil fuels. The storage of biodiesel in extreme cold winters may increase the water present in the fuel that further affects freezing and combustion temperatures paramount for engine performance.

Initiatives taken by the Indian Government:

SATAT:

In October, 2018, Sustainable Alternative Towards Affordable Transportation (SATAT) scheme was launched to promote use of Compressed Bio Gas (CBG). SATAT initiative envisages establishing 5000 Compressed Bio Gas (CBG) plants across the country by 2023 (https://pib.gov.in/PressReleasePage.aspx?PRID=1843441)

NATIONAL POLICY ON BIOFUELS, 2018:

The Policy categorizes biofuels as "Basic Biofuels" viz. First Generation (bioethanol & biodiesel) and "Advanced Biofuels" - Second Generation (ethanol, Municipal Solid Waste to drop-in fuels), Third Generation (3G)

biofuels (bio-CNG) to extend the monetary rewards and tax breaks under all these category. It also widens the scope of basic raw material for production of ethanol by allowing use of juice extracted from sugarcane, sugar containing plant materials like sweet sorghum, sugar beet, starch containing plant materials like cassava, corn, damaged food grains like broken rice, wheat, rotten potatoes, that are unfit for human consumption for ethanol production. This Policy also allows utilization of surplus food grains for ethanol production by blending with petrol with the approval of National Biofuel Coordination Committee. Moreover, the Policy reflects a viability gap funding scheme for 2G ethanol Bio refineries in addition to additional tax incentives, higher purchase price as compared to 1G biofuels. The Policy encourages setting up of supply chain mechanisms for biodiesel production from non-edible oilseeds, used cooking oil, short gestation crops. Roles and responsibilities of all the concerned Ministries/Departments concerned with respect to biofuels have also been captured in the Policy. (https://pib.gov.in/PressReleasePage.aspx?PRID=2043926)

PRADHAN MANTRI JI-VAN YOJANA:

In March, 2019, Government notified the 'Pradhan Mantri JI-VAN (Jaiv Indhan- Vatavaran Anukool fasal awashesh Nivaran) Yojana' for providing financial support to integrated bioethanol projects for setting up second generation ethanol projects in the country using lingo-cellulosic biomass and other renewable feedstock. The key objective is to allure greater investment and the latest advancements in 2G ethanol capacity in the country. It would have a wider scope for biofuels that are derived from agricultural and forestry residues, syngas, industrial waste, and algae. In order to emphasize on innovation, this scheme will also prioritize project proposals introducing novel technologies and use a wide array of feedstock. It aims at providing hefty incomes for farmers, curtailing environmental pollution, creating local employment opportunities, and supporting India’s energy security and self-reliance. The government of India has envisioned a sustainable and an energy self-sufficient future by supporting advancements in biofuel production technologies, Make-in-India Mission along with a targeted goal of net-zero GHG emissions by 2070.

(https://mopng.gov.in/files/uploads/BPCL_Ethanol_Booklet_2023.pdf).

ETHANOL BLENDING PROGRAMME (EBP):

This programme aims at mitigating the country’s dependency on the imports of crude oil along with reducing the carbon emissions and boosting the incomes of the farmers. The Government of India aims to blend ethanol with petrol with a current target of 20% blending by 2030. In fact, the government had also reduced the GST on ethanol for blending in fuel from 18% to 5%.

This program is a part of the National Biofuel Policy 2018. For its implementation, various Oil Marketing Companies (OMCs) sell blended petrol under EBP. When implemented thoroughly, it can reduce foreign exchange outflow, support rural income and lower greenhouse gas emissions. Furthermore, the government has also a scheme to provide monetary assistance to sugar mills for increasing ethanol production capacity. (https://mopng.gov.in/en/refining/ethanol-blended-petrol).

Notable Projects in India

- The first 2G ethanol project initiated by Indian Oil Corporation Limited in Panipat, Haryana, was inaugurated by worthy Prime Minister on August 10, 2022.
- Other 2G projects by HPCL, BPCL, and NRL in Bargarh (Odisha), Bathinda (Punjab), and Numaligarh (Assam) are about to be completed.

Conclusions

Through this chapter, we discussed about the reasons for biofuel production as it is an immediate and long-term measure to limit the GHG emissions. However, biofuels are not going to be the sole solution to combat this prevalent issue, but can contribute significantly in association with other technologies that can cohesively provide carbon neutral or carbon negative energy. As far as transportation is concerned, biofuels ought to act in alliance with electric vehicles. Apart from biofuel manufacturing, some other carbon dioxide fixation processes could also be implemented in other sectors. To corroborate, yeast and algal oil can be transformed into building materials such as cement additives and carbon fibers as the atmospheric CO_2 can be absorbed from the environment through these routes, and stored for a longer period of time. Such technologies could complement materials derived from fossil fuels or that generate large amounts of CO_2 during the manufacturing process (e.g., steel, aluminium and concrete) (Tse et al., 2021). We are convinced that, in the last decades, mankind has been generally too hesitant to adopt climate-centered technologies, which has put the world on a perilous pathway toward catastrophic climate change (Vamsi et al., 2022; Xin et al, 2016). It has become the need of the hour to take due action to resort climate issues through effective and efficient technologies available on the global front. It is highly imperative to implement large-scale infrastructure for the production of sustainable and renewable energy carriers. Moreover, the production strategies can be improvised from time-to-time in the upcoming scenario and for this, a closely-knitted academic and industrial partnership is required. Even beyond the scientific communities, the general public is

curious and ready to accept the drastic changes in order to curtail the climate change repercussions and to become a sustainable society.

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CHAPTER-15

NANOTECHNOLOGY FOR SUSTAINABLE AGRICULTURE AND FOOD SECURITY: INNOVATIONS, APPLICATIONS AND FUTURE PROSPECTS

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Abstract

The agricultural sector is a cornerstone for any developing countries' economy. With the continuous growth in population worldwide, pressure on agriculture to meet food security challenges has been immense. Nanotechnology is an innovative solution to overcome food security and agricultural sustainability challenges. Nanotechnology introduces environmentally friendly approaches to pest and insect management and enhances crop yield and efficiency of plants' nutrient uptake. Nanoformulated insecticides and pesticides have been found to have increased solubility, mobilization, and stability in agricultural use. Nanotechnology incorporation in agriculture could improve productivity, prevent pest, and weed contamination, water use efficiency and retention, abiotic stress tolerance and minimize adverse effects on soil, water, and human health. Still, concerns about safety, toxicity, risk assessment, risk management and sub-par regulatory

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frameworks hinder from large-scale application of nanotechnology in agriculture. This chapter discusses nanotechnology applications in agricultural sector with a view to its potentials towards sustainability and food security.

Keywords: Nanotechnology, Nanoparticles, Agriculture, Food Sciences, Environmental Sciences, Sustainability.

Introduction

Agricultural growth is an important driver for economic growth, especially in developing nations. The world population is increasing exponentially and is widening the gap between demand and availability of agricultural produce. For solving this problem, emerging technologies need to be added to the toolbox of agricultural activities (Abbas et al., 2016). Nanotechnology can become a game-changer in agricultural productivity as well as food processing and packaging (Agrawal and Rathore, 2014). Nanotechnology is making its mark in society with its diverse applications and since 2003 its entry into the agriculture and food sectors has helped promote research in agri-nanotechnology in recent years.

Nanotechnology pervasively affects virtually every area of agriculture ranging from plant and soil health to irrigation management, water purification, food processing, packaging, and pest management. Nanotechnology allows nanoscale structures to be fabricated through modification of materials at an atomic level (Aouada and De Moura, 2015). The main application areas of nanomaterials and nanotechnology in agronomy are to enhance crop yield, regulate nutrient loss, and minimize the use of chemicals through effective pest and nutrient management. By 2020, nanotechnology's global economic influence was forecasted to be over 3 trillion US dollars while about six million workers were engaged in production, marketing, and quality assurance of nano-based products and in enhancing food efficiency and safety (Aziz et al., 2016).

Nanotechnology: Definition

Nanotechnology is broadly described as the science involved in handling and using materials at an extremely small dimension—namely, one-billionth of a meter (Poddar et al., 2018). The name comes from "small" or "dwarf" in Latin and is an unprecedented breakthrough over conventional technologies because of its infinitesimal dimension and scope. Some of the primary features of nanotechnology comprise nanodevice fabrication and nanoparticle (NPs) manipulation. The definition of NPs as materials with one dimension in the approximate size range 1–100 nanometers is given by the United States Environmental Protection Agency, while for the European Union, the

definition includes natural, incidental, or manufactured particles with 50% of their size in the same approximate size range.

They can be characterized structurally (e.g., nanocrystals, nanostructures), or dimensionally (0D, 1D, 2D, or 3D). Properties change significantly based on variables such as chirality (e.g., carbon nanotubes might be semiconductors or metals) (Saito and Zettl, 2008). Nanomaterials might be found naturally, engineered in certain conditions, or formed through self-assembly (Monica and Cremonini, 2009).

Biosynthesis of Nanoparticles

Nanoparticles are tiny structures smaller than everyday objects but greater than single atoms and work according to quantum principles. Nanoparticles can be synthesized using different physical and chemical processes; however, these processes tend to be very costly and labor-consuming and are environmentally toxic. To counter all these shortcomings, biosynthesis is proving itself to be a viable and sustainable method. Plants, bacteria, fungi, and yeast are increasingly being utilized to synthesize nanoparticles because they are environmentally friendly and cost-effective.

Green Synthesis of Nanoparticles

Characteristics of green synthesis processes include their cost-effectiveness, benign nature towards the environment, low toxicity, and high rates of reaction (Berekaa, 2015). Physical and chemical approach to synthesis of Nanoparticles turn out to be costly and involve implications detrimental to health and environment. Moreover, factors including low growth rates and lack of well-defined structures during nanoparticle formation as well as toxicity of synthesized materials are major concerns (Das et al., 2015; De Matteis, 2018). Green synthesis is conducted by mixing plant extracts with appropriate metal ions in exact proportions under controlled physical conditions (Ditta and Arshad, 2016). Green synthesis of metal nanoparticles makes use of an array of organic materials that could be plants or microorganisms.

Nanoparticles from Plants

Plants have been employed to synthesize nanoparticles due to their diverse phytochemicals including terpenoids, ascorbic acids, aldehydes, flavones, ketones, and amides from within their plant extracts (Pandey, 2020). Plant phytochemicals have the capacity to reduce metal salts into their respective metallic nanomaterials. Green synthesis of nanomaterials is an effective single-step biological reduction process that is energy-efficient compared to their chemical and physical counterparts (Hajirostamlo et al., 2015). Plant

species can be used as biofactories for synthesizing metal nanomaterials using their reducing property contained in the cell sap or extract. Gold nanomaterials (Au NPs) have been synthesized successfully in gold-salt containing media in alfalfa species and *Sesbania* seedlings (Gardea-Torresdey et al., 2002; Sharma et al., 2007). Silver nanomaterials (Ag NPs), too, have been synthesized using metallophytes including *Brassica juncea*, *Medicago sativa*, and Alfalfa sprouts (Harris and Bali, 2008). Silver nanomaterials have also been synthesized by mixing plant leaf extracts with silver nitrate ($AgNO_3$) solutions in quick syntheses using plant leaves including pine, persimmon, ginkgo, magnolia, and platanus (Song and Kim, 2009). Semiaquatic plants in symbiotic association with endomycorrhizal fungi at the root-soil interface also support copper biomineralization and yield copper nanomaterials (Cu NPs). Green approaches using plants have been shown to hold prospects for sustainable nanomaterial synthesis through environmentally friendly pathways as an alternative to conventional approaches.

Nanoparticles from Microbes

Microorganisms possess the capability to bioreduce metal ions into single-crystal metal nanoparticles using extracellular enzymes. Bacteria and fungi, due to their specific affinity towards metals, are extremely valuable for green synthesis of metal nanoparticles. While nanoparticle synthesis using microbes is slower than those using plants, microbes provide advantages in manipulating the product easily due to their simple growth and culture modes, low capital expenditure requirements, and minimum environmental hazards (Jayaseelan et al., 2011; Handford et al., 2015).

Bacteria

Bacteria as prokaryotic cells easily undergo genetic modification to enable nanoparticle synthesis. Bacteria have been widely utilized to synthesize silver, gold, zinc, lead, iron, iron sulfide, and cadmium quantum dots (Khan and Fulekar, 2016).

Fungi

Fungi have been recent entrants into nanoparticle synthesis but have greater advantages over bacteria in that they are easy to manage, have high enzyme production yield, and have easy downstream processing. Genetic modifications in fungi are more difficult though (Karpachev et al., 2016).

Nanotechnology and Sustainable Agriculture

In developing nations, agriculture faces numerous challenges, including uncertain climatic conditions, bioaccumulation, high-speed industrialisation and increasing food demand arising because of an estimated global population of six to nine billion in 2050 (Kouhkan et al., 2020). The agricultural sector is plagued by stagnating crop yields, nutrient deficiencies, organic matter decline in soil, climate change, diminishing arable land, water shortage, GMO resistance, and shortage of labor (Mani and Mondal, 2016). In India, for instance, the Green Revolution's lasting consequences are seen as fertilizer use skyrocketed from 0.5 million tons in 1960 to 23 million tons in 2008 (Liu and Lal, 2015; Mabe et al., 2017). While crop yield rose four times, over-dependence on fertilisers resulted in a decline in soil organic matter leading to plateauing crop yields after some time. Advancing agriculture is one of the best means to combat poverty and feed an estimated global population of nine billion by 2050. Growth in agriculture is an important generator of income for poor people and is central to economic growth and food security, especially when climate change disproportionately acts on food-insecure areas. Public health is also influenced by current agricultural practices as 70% of agricultural water use generates undesirable water pollution and wastage. About three billion people experience health emergencies due to insufficient food and lack of adequate nutrition.

Nanotechnology holds immense potential in agriculture with nanoparticle incorporation in plants resulting in structural and physiological modifications leading to enhanced growth, seed germination, and yield. Nanotechnology is poised to find numerous applications in agriculture ranging from precision agriculture and nanobiotechnology. Previous applications in agriculture ranged from using porous soil and clay for filtration and purification of water but now center on crop defence and gradual release of nutrients. New applications like using nanoparticles (NPs) for plant growth in soilless media are becoming increasingly popular and are likely to gain momentum in the near future.

Nanotechnology is now an essential part of agriculture, providing cutting-edge solutions for tracking growth in plants as well as disease detection. The major advantages of nanotechnology encompass better pest management using pesticide nanoformulations, increased productivity through nanoencapsulation of fertilizers for controlled release of nutrients, pest resistance through nano-mediated transfer of genes and nanobiosensors for precision agriculture (Burhan et al., 2019).

Increasing adoption of nanotechnology in various fields has been prompted by huge investments facilitated by academic research work and contributions

from leading food companies and governments. This chapter discusses nanotechnology applications in agriculture and its possible advantages and related hazards.

Application of Nanotechnology to Sustainable Agriculture

Different nanoparticles have been researched on their capacity to enhance crop yield, root, and shoot growth, root-to-shoot ratios, fruit growth, and nutrient acquisition (Nair et al., 2010). NPs influence crop mineral nutrition by changing enzymatic activity and electron transfer chains, inducing changes in plant physiology. NP uptake through seeds, seedlings (Lin and Xing, 2008), roots, pollen grains (Speranza et al., 2010), cellulose-walled plant cells (Liu et al., 2009), direct injections (González-Melendi et al., 2008), and aerosol-based sprays on seedlings and leaves (Anusuya and Sathiyabama, 2025) has been well researched.

Enhancing Seed Germination through Nanotechnology

Seed germination is an important aspect in effective crop production since it plays a key role in plant emergence and early growth. Germination is difficult in soils with high salinity. Enhanced germination is likely to result in more powerful early growth and enhanced plant establishment. Lentil genotypes exhibited enhanced germination and seedling growth after application of SiO_2 NPs (Sabaghnia and Janmohammadi, 2015). Nanoparticles also affect the physiological and molecular processes in plants to improve seed germination and seedling growth. Spinach seeds treated with TiO_2 grew 45% more chlorophyll-a with an increase in photosynthesis by threefold and 73% increase in 30 days' dry weight (Zheng et al., 2005). Comparable results have been reported in TiO_2 nanoentity-treated wheat (Feizi et al., 2012), increasing water and nutrient uptake and consumption, reducing reactive oxygen species, and degrading organic matter. Surprisingly, smaller-sized nanoparticles were correlated with better germination.

Nevertheless, TiO_2 nanoparticles can be potentially hazardous to human health. Gold nanoparticles (AuNPs) have been proposed as a less hazardous substitute and produced germination rates as high as 95% (Mishra et al., 2019). Carbon nanotubes (CNTs), specifically multiwalled CNTs (MWCNTs), have been proven to enhance seed germination and plant growth. Tomato seeds treated with MWCNTs (10–40 μg/mL) recorded improved germination percentage, seedling biomass, and root and stem elongation compared to untreated controls (Khodakovskaya et al., 2009).

Other metal nanomaterials such as silicon (Si), copper (Cu), palladium (Pd), and gold (Au), too, show positive responses towards seed germination. For

instance, Si and Cu NPs increase germination at high concentration, whereas Pd and Au NPs have similar effects at low concentration (Shah and Belozerova, 2009). Nanoparticle responses vary enormously depending on nanomaterial and crop species and need to be further explored at a cellular level. Although nanotechnology significantly benefits germination processes, phytotoxicity is a concern as its efficacy is dependent upon nanomaterial types being used. For instance, fluorescein isothiocyanate (FTIC)-tagged silica nanomaterials enhance germination, while cadmium selenide (CdSe) quantum dots inhibit germination (Nair et al., 2011). In the future, further progress in nanotechnology might help enhance seed germination, especially in arid and drought areas, offering novel solutions towards increasing food security worldwide.

Nanotechnology in Plant Disease Management

Nanotechnology is proving to be an effective tool in plant disease management and plant health promotion, but its application is still in its infancy stage (Elmer and White, 2018). Chitosan a natural polysaccharide with diverse molecular weight is found to be effective in inhibiting growth of *Botrytis cinerea*, a post-harvest pathogen causing gray mold disease resulting in considerable losses in fruits and vegetables during storage in *in vivo* and *in vitro* trials. When blended with nanomaterials such as nano-ZnO, nano-$CaCO_3$, and nano-silicon, chitosan films inhibit decay, respiration rate, weight loss, and spoilage in coated produce.

Among various NPs, silver nanoparticles (AgNPs) have shown the most potential in disease control (Alghuthaymi et al., 2015). AgNPs disrupt oxygen metabolism in bacteria and fungi, ultimately leading to microbial death. Additionally, they can damage cellular DNA, elevate reactive oxygen species (ROS) levels, interfere with the electron transport chain, and inhibit nutrient uptake by pathogens. Silver-silica (Ag-SiO_2) NPs have proven highly effective against a range of phytopathogenic fungi, including *Alternaria solani*, *Botrytis cinerea*, *Bipolaris sorokiniana*, *Aspergillus niger*, *Colletotrichum gloeosporioides*, *Fusarium oxysporum*, *F. solani*, *Glomerella singulata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Rhizoctonia solani*, and *Phoma glomerata* (Jo et al., 2009; Kim et al., 2012; Mishra et al., 2014).

Other nanomaterials, including ZnO and $ZnTiO_3$, also exhibit high antimicrobial activity (Ruffolo et al., 2010). 100 ppm nanosized silica-silver completely inhibited growth of bacterial pathogens including *Pseudomonas syringae* and *Xanthomonas campestris* pv. *vesicatoria* (Park et al., 2006). For greater improvement in activity of silver NPs, graphene oxide as a support

material for NP accumulation on bacterial surfaces has been explored. This resulted in more potent antibacterial activity against *Xanthomonas perforans*, a pathogen causing bacterial spot in tomato (Ocsoy et al., 2013).

A copper nanoformulation successfully controlled bacterial blight induced by *Xanthomonas oryzae* pv. *oryzae* in rice and mung bean leaf spot induced by *X. campestris* pv. *phaseoli* (Gogoi et al., 2009). Copper NPs at 200 g/L inhibited growth of fungal pathogens including *Aspergillus niger*, *Aspergillus flavus*, *Penicillium chrysogenum*, *Fusarium solani*, and *Alternaria solani* (Essa and Khallaf, 2016). Although used extensively in other industries, these NPs have been slow to be launched in agriculture on a large scale. A crucial step towards that goal came in 2011 when the EPA conditionally registered "nanosilver pesticide," but as an antimicrobial on textiles and not in agriculture.

Nanopesticides

The term "nano" in relation to pesticides lacks a precise definition. Products labeled as "nanohybrid," "nanocomposite," "nanoemulsions," and "nanodispersion" are grouped under nanopesticides, even if they do not always fall strictly within the traditional nanoscale. Nonetheless, they exhibit traits commonly linked to small particle sizes.

Nanopesticides are generally divided into two main categories. The first includes nanomaterials that naturally have pesticidal activity—these are usually inorganic substances like nanosilica, nanotitanium dioxide, nanozinc, nanosilver, nanocopper, and nanoaluminum (Kah and Hofmann, 2014). These materials have shown effectiveness, for instance, silica and aluminum nanoparticles have been linked to higher insect mortality, while nanosilver and nanocopper are known for their antimicrobial capabilities (Stadler et al., 2010; Debnath et al., 2011; Mondal and Mani, 2012).

The second category involves nanopesticide formulations, which have gained foothold in recent years. These formulations typically rely on organic nanomaterials and make use of nanoencapsulation techniques to enhance pesticide delivery. Major chemical companies are now developing pesticide products at the nanoscale for precise and targeted release (De Oliveira et al., 2021). Studies show that nanoformulations of pesticides like imidacloprid, thiamethoxam, thiram, and carbofuran tend to have longer-lasting effects and greater stability (Adak et al., 2012). Nanoemulsions made with pesticides such as neem oil, acephate, and glyphosate have also shown better target-specific action than their conventional counterparts (Anjali et al., 2012; Jiang et al., 2012). Additionally, nanocomposites infused with pheromones and

essential oils have been successfully developed against insect pests (Bhagat et al., 2013; Abreu et al., 2020).

Proponents emphasize the precision and specificity of nanopesticides as their tiny size vs. surface area improves contact with pests and boosts absorption. Nanoformulations can enhance the solubility of pesticides that are otherwise hard to dissolve, support controlled or slow release of active compounds, protect them from environmental degradation (Kah, 2015). Despite these advantages, high production costs remain a major obstacle to their widespread use. While nanotechnology is widely accepted in areas like cosmetics and food additives, nanopesticides continue to raise concerns due to increased mobility, persistence, and potential toxicity leading to unforeseen soil and environmental contamination. As a result, there's growing interest in greener, biopolymer-based delivery systems, which appear promising. However, regulatory frameworks in many countries are still not fully equipped to address the unique challenges posed by nanomaterials.

Abiotic Stress Tolerance

Nanoparticles (NPs) play a crucial role in boosting germination and seedling development under stressful environmental conditions. This positive effect may be attributed to increased water content in the xylem, improved water transport, or more efficient nutrient uptake. Silicon dioxide (SiO_2) nanoparticles significantly enhanced germination rates, shoot and root lengths, and overall seedling biomass in lentil plants exposed to salt stress (Sabaghnia and Janmohammadi, 2014). Silicon is also well-regarded for strengthening plants against biotic stress, reducing heavy metal toxicity, and enhancing structural resilience. However, excessive silicon can become harmful, especially in acidic soils. Compared to salt-based formulations, colloidal nanoparticles are up to forty times less toxic, making them a safer and more effective option for improving plant productivity.

Getting the concentration of NP solutions right is key to achieving optimal outcomes. Research by Taran et al. (2017) found that colloidal copper (Cu) and zinc (Zn) nanoparticles helped mitigate drought stress in winter wheat by enhancing the activity of antioxidant enzymes. This led to reduced levels of oxidative damage indicators, improved water retention in leaves, and higher concentrations of photosynthetic pigments. Carbon nanotubes (CNTs) have also shown promise in increasing plant tolerance to salt stress. Specifically, multi-walled carbon nanotubes (MWCNTs) improved both water absorption and carbon dioxide (CO_2) assimilation in broccoli plants treated with sodium chloride (NaCl) (Martínez-Ballesta et al., 2016).

Nanofertilizers

Nanotechnology-driven fertilizers exhibit excellent capability in enhancing plant growth and agricultural yield (Kim et al., 2018). Performance phosphate products (PPPs) and conventional fertilizers do not achieve their target due to environmental volatility (Solanki et al., 2015). Smart nano-based delivery systems overcome this challenge by increasing fertilizer efficiency and specificity (Chhipa et al., 2017). These systems stabilize the chemicals and allow controlled and prolonged release of nutrients (Rohela et al., 2019), and minimize soil contamination and eutrophication (Wilson et al., 2008). Nano-fertilizers prevent nitrogen loss through emission, leaching, and microbial activity and adjust nutrient availability according to crop demands (Fortunati et al., 2019).

Slow-release fertilizers involving those with added natural zeolites are viable substitutes for traditional soluble fertilizers. Nanomembranes may be applied as fertilizer particles to provide slow and sustained nutrient release (Kothari et al., 2023). Patented nanocomposites involving substances such as phosphorus, potassium, nitrogen, amino acids, and micronutrients have been synthesized to ensure nutrient and yield improvement (Abd El-Aziz et al., 2019).

Nano-sized agrochemicals like zinc oxide (ZnO) nanomaterials have shown that they improve growth in stems, roots, and pods better than zinc sulfate (Prasad et al., 2012). Combinations of SiO_2-TiO_2 have been seen to increase nitrate reductase activity in soybeans, leading to more effective nutrient uptake. In an analogous manner, iron oxide nanomaterials (Fe_2O_3) have proven to be good fertilizers. Applied as maghemite (γ-Fe_2O_3), they enhanced peanut height over chelated iron fertilizers. These treatments also enhanced chlorophyll levels, photosynthesis activity, and growth hormones such as gibberellins and zeatin-riboside while decreasing abscisic acid (ABA) stress hormone level (Rui et al., 2016). While nanofertilizers hold great promise additional research is necessary to render nanoencapsulated fertilizer application cost-effective.

Improvement of Photosynthetic Efficiency

Nanoparticles (NPs) have been proven to increase photosynthetic efficiency in vegetation by regulating the dark and light reactions in photosynthesis. With high ratio of surface area to volume, NPs enhance the phase of the light reaction by their interplay with specific wavelengths of light. Such a property is indispensable for photosynthesis-dependent light reactions, including the Hill reaction involving photosystem I or II (Noji et al., 2011). For example, exposing aging spinach seeds to nano-TiO_2 resulted in an increase in chlorophyll-a content by 45%, leading to three times greater photosynthesis

(Zheng et al., 2005). Its most prominent application is enhancing absorbance of light and stimulating the activation of RUBISCO activase, thus maximizing total photosynthetic capacity. Such an innovation increases sugar production through the Calvin cycle and hence enhances photosynthesis as well as food reserve storage. Such improved photosynthetic efficiency goes beyond promoting food yield to making the sink mechanism in the plant for storing synthesized sugars stronger as well.

Enhancing Water Use Efficiency (WUE) and Water Retention

Agriculture is the largest water user in the world and water use efficiency (WUE) improvement is essential to achieve sustainable crop growth, particularly in water-deficit areas. Nanoparticles exhibit high promise in increasing WUE for instance, titanium dioxide (TiO_2) nanoparticles decrease root hydraulic conductivity in corn seedlings and carbon nanotubes enhance water intake and transpiration in plants.

Cerium oxide nanoparticles have been especially effective in boosting RUBISCO activity, photosynthesis rates, and WUE in crops including soybeans and tomatoes (Cao et al., 2017). They have also promoted growth and yield in wheat (*Triticum aestivum* L.). Gold nanoparticles with good adsorption capacities have further promoted WUE while being less hazardous. Crops enriched with nanoparticles including cerium oxide, titanium oxide, and silver are especially ideal for water-scarce regions including deserts as they consume less water while being highly efficient.

Optimized use and avoidance of losses during irrigation are major issues in sustainable agriculture. Nanomaterials including carbon nanotubes (CNTs) have been reported to increase water holding capacity (Khodakovskaya et al., 2012). This increase is due to improved xylem vessel functioning, regulated plant metabolism, and strengthening of sieve tube mechanisms resulting in improved biomass and fruit yields. For instance, application with multi-walled carbon nanotubes (MWCNTs) greatly enhanced water uptake and growth in pumpkin (Corredor et al., 2009) and broccoli (Martínez-Ballesta et al., 2016). By increasing aquaporins—major water pore proteins—carbon nanotubes have been employed to enhance water uptake in tomato root cell walls (Villagarcia et al., 2012).

Groundwater management, soil stabilization and reducing ecotoxicity are also areas that nanotechnology holds out hope for. Work on decontaminating groundwater through zero-valent iron nanoparticles (NPs) started in the 1990s. They have been found to be one hundred times more reactive than their macroscopic counterparts. Carbon nanotubes, nanometal oxides, nanoenzymes, and bimetallic NPs have all been found to be effective for decontaminating groundwater.

Monitoring Field Conditions

In organic cultivation, remote sensors, GPS technology, and computing technologies monitor environmental conditions so that crops grow in ideal conditions (Misra et al., 2013). Nanotechnology provides novel solutions for real-time observation of field conditions and crop growth through smart sensor technology. These technologies monitor parameters including temperature, light intensity, soil wetness, fertility, nutrient availability, occurrence of weeds, insects, and plant pests (Dasgupta et al., 2017). Precision agriculture for obtaining maximum yield while reducing fertiliser use, herbicides, and pesticides is significantly facilitated by nano-sensors. These sensors also minimize agricultural pollution and improve crop yield. Nonetheless, despite all these benefits, concerns regarding the biosafety of nanobiomaterials in sensing structures remain. Sufficient research is required to determine and alleviate the nanotechnology-based sensing system-related dangers.

Concerns about Nanotechnology

Legal and Regulatory Concerns

The enhanced interest in using nanotechnology for agriculture is met with incoherent legal structures worldwide. Nanoentities and nanoscale reformulation of existing chemicals in nations such as India and Thailand are almost impossible to patent due to legislations such as Section 3(d) of India's Patent Act that delineates such innovations as "evergreening" practices (Basheer and Reddy, 2008). This hampers the prospect for protecting and building nanofortified products, e.g., moisture-retentive nanoparticle clays, and inhibits innovation in green agriculture.

At an international level, regulatory bodies do not differentiate among naturally formed nanoentities and synthesized nanoentities. For instance, EU regulations do not distinguish between materials formed in nature and nanoproducts that have been scientifically designed (Bowman and Hodge, 2006). Stronger regulatory structures and common protocols, similar to those employed by FDA for clinical devices, must be developed for nanotechnology applications in agriculture.

Socioeconomic Concerns

The economic and sociological implications of nanotechnology in agriculture parallel those for current agricultural technologies with an emphasis on commercial success and sustainability. Nanotechnology enhances

agrochemical performance, increases soil and water distribution efficiency, and prolongs shelf life. Its adoption is challenged by chances for patent battles resulting from overlapping innovations. Label transparency and regulating markets are especially important in allowing informed consumer choice and promoting sustainable practice and production principles.

Toxicological and environmental concerns

Although nanotechnology has a wide array of benefits, nanoparticle (NP) safety in biological systems is a concern. Excessive use of nanopesticides and nanofungicides introduces contaminants into the environment (soil, water, and air) and food chain bioaccumulation. Dose-dependent toxicity of nanomaterials, including aluminum and zinc oxide, towards crops including corn, carrots, and soybeans on root growth, biomass, and seed germination has been reported in research (Li et al., 2015). Nanomaterials including nano-ZnO and nano-CeO_2 also deposit in edible plant tissues and affect food quality and yield (Priester et al., 2012).

Their small size enables them to invade plant structures such as stomata and disrupt their physiological processes and their possible integration into genomes generates genetic toxicity concerns. In animals, NPs may result in inflammatory, respiratory, and hematologic disorders. Environmental implications in terms of changes in soil and water holding capacity over a period of time are also noteworthy. Risk assessment regarding NPs is making progress despite existing gaps in data worldwide (FAO/WHO, 2013). Safe and regulated application of nanoentities must take place to maximise their benefits while reducing risks.

Conclusion

Science relies heavily on innovative technologies and methodologies, and nanotechnology has presented a revolutionary tool box that is propelling biological, medical, and physical sciences forward. Nanotechnology is driving innovations in applications such as food production, pollution management, genetic modification, water purification, and medical sciences, resulting in enhanced quality of life. In agriculture, it improves packaging, storage, and precision agriculture through controlled fertilizer and pesticide delivery, insecticides, and plant growth promoters. It also enhances the nutritional quality and shelf life of foods. Although nanotechnology is full of promise for agriculture and food security, its unforeseen health dangers and security implications need to be addressed to allow its safe and responsible application.

Nanotechnology also holds tremendous potential for sustainable agriculture if implemented in an appropriate regulatory framework to guarantee environmental safety and economic viability. The increasing interest in nanotechnology indicates a movement towards precision agriculture and its chances to redefine agricultural productivity at reasonable costs. Deep ethical, toxicology, and regulatory issues need to be tackled with more research, sufficient funds, and proper policy support. With the creation of environmentally safe nano agricultural schemes, nanotechnology can eliminate existing hurdles and opening up avenues towards a sustainable and innovative agricultural future.

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CHAPTER-16

SUSTAINABLE FARMING FOR FOOD SECURITY

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Abstract

Farmers are the backbone and the foundation of agriculture and food sector. They have a crucial role to play in feeding the population worldwide. Under the pressure of feeding the growing population, farmers globally experience diverse challenges, such as environmental degradation, natural disaster, climate change, economic instability, political instability, accessibility to markets, farming practices, use of technologies etc. Empowerment of farmers thus is a necessity in building sustainable food systems, improving livelihoods, and ensuring food security for all. This article explores the importance of empowering farmers- the real cog in the wheel of global food security, besides, illustrates strategies that can enable the sustainable development of farmers in today's era of innovation like adoption of sustainable, ethical and organic farming practices. Sustainable methods for farming are crucial for ensuring food for all even when challenges come across. It aims to increase food production along with the wellbeing of the ecosystem for sustainability. Sustainability demands judicious use of resources, increase in production besides preventing contamination of soil. Organic farming is the approach which takes care of ethical and sustainable aspect as it improves soil fertility, and maintain biodiversity along with the production of healthy food. This chapter went through literature review and is an attempt to address the indispensable role of farmer empowerment, use of ethical and organic farming techniques along with the use of technology for sustainable agriculture to tackle the issue of global food security keeping in mind the environmental wellbeing.

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Introduction

Food is the basic requirement of all living beings. The green revolution which aimed to feed the growing world population with the use of technology, fertilizers, hybrid variety of seed brought about tremendous increase in food production over last couple of decades but it has also posed serious threats to environment with the use of fertilizers etc. (Cioffo et al., 2016; Glaeser, 2010; Wijerathna & Pathirana, 2022). Crop yields are obtained at the cost of environmental degradation, however without the use of fertilizers, production reduces considerably. With the increase in population, demand for food increases. Food prices too have rose rapidly in last few decades (Kneafsey et al., 2013).

Natural disaster, climate change and its impact have adverse effects on the agricultural output in developing countries where agriculture depends mostly on rainfall (Olawale et al., 2023). Climate change resulted in extreme weather events like floods, drought, heat waves, storms etc. pose serious threat to crop production (Habib-ur-Rahman et al., 2022) and raise concerns of food supply to the growing demands globally. A study (Venkatappa et al. 2021) shows that natural calamities like floods and drought have adversely affected the crops in southeast Asia. Natural disaster and climate change lead to less production of crops and hence contribute to food insecurity in various parts of the world especially developing countries. Besides, economic and political instability too have adverse effects on agricultural yields. Political instability poses another threat to agriculture production. Studies (Asfew et al., 2023; Grote, 2014; Soffiantini, 2020; Warsame et al., 2023) show that various regions across globe are affected by the political instability in addition to the socio-economic factors. Ever increasing demands along with the above-mentioned challenges put farmers in tough situations to live upto the scenario. This exerts pressure on them along with available resources, so the need for sustainable agricultural practices becomes vital. Empowering farmers is crucial in the development of strategies to meet the growing demands. Studies (Hanggana, 2024; Kaur et al., 2024; Siaton et al., 2024; Uphoff, 2012) disclose the requisite and effectiveness of various farmer empowerment strategies like unifying agricultural land, farm produce commercialization systems and facilitating access to scientific knowledge and technology, promoting organic and ethical farming for sustainable food security. Further to understand the intersection of sustainability, ethical, and organic practices in food security, it is important to define these concepts.

- **Sustainability** in agriculture sector refer to farming practices that make food production convenient today and always, without compromising the availability of resources for the future generations. Sustainable agriculture (Reganold et al., 1990) does not refer to using traditional methods of agriculture rather using the ecofriendly methods with state-of-the-art technology to meet the increasing needs and ensuring economic viability for farmers. Sustainable practices aim to minimize environmental degradation besides conserving resources.
- **Ethical practices** in agriculture refers to the attitude, preference and decisions while processing the agricultural activities to increase crop production and sale. Environmental as well as human health damage caused as a result of various agriculture sector activities highlights the need to reconsider the techniques for crop production, management and marketing (Sanford, 2011).
- **Organic practices** in agriculture (Gamage et al., 2023; Merrigan et al., 2022) refers to the farming processes that avoids the use of fertilizers, pesticides etc. which have negative effect on the environment. Organic farming rather prefers the processes like crop rotation, animal manures etc. other natural nutrient sources during the process of crop production. Additionally, organic agriculture aims to maintain the health of soils, ecosystems, and people.

Sustainable, Ethical, and Organic farming practices for global food security

Sustainable agriculture (MacRae et al., 1989; Reganold et al., 1990; Velten et al., 2015) consists of various forms of nontraditional farming, often referred to as organic, alternative or ecofriendly farming. A sustainable farming method is the one which ensure to generate sufficient amount of high-quality food, protect its resources, and maintain ecological balance besides earning profit. Rather than relying on external inputs like fertilizers, pesticides etc. to increase crop yield, sustainable farming prioritizes utilizing natural resources. Organic matter present in the soil consisting of plant and animal waste besides other microbial presence is very important to increase the fertility naturally in organic farming (Palaniappan & Annadurai, 2018). If the country wishes to promote organic farming, then it has to provide subsidizes to the farmers using the ecofriendly methods besides giving incentives.

Moreover, sustainable development requires change and empowerment of various sectors of society. Studies (Kusnandar et al., 2019) reveal that the main factors that influence sustainable agricultural development and

production are environmental, economic, social and governance-related. Majority of the initiatives taken are focusing on economic factors to encourage farmers to opt for organic practices. Meanwhile, the social aspect is not given much consideration. The social domain of agriculture sector which involve the land, labour, yield, transportation and marketing etc. in the process of production to management needs consideration for sustainable practices.

The literature (Hansen, 1996; Thompson, 2007; Trigo et al., 2021) presents two primary interpretations of sustainable agriculture. One perspective views sustainability as the recognition of the harmful effects of traditional agricultural practices, while the other sees it as a collection of strategies aimed at improving adaptability by strengthening the system to ensure food security.

- Important factors for facilitating sustainable agriculture
- Increasing environmental awareness among different sections of society
- Knowledge regarding the link between diet and health
- Awareness about potential diseases linked with farming practices
- Viable options available for heathy production of crops
- Introduction of innovative methods for crop production using science and technology
- Need to put less pressure on available resources

These factors must be considered and addressed in the process of transitioning to sustainable food systems which effect the farmers, the society and the ecosystem. Reports reveal (Gliessman & Rosemeyer, 2009) that sometimes farmers experience reduced yields and profits during the first couple of years of these farming practices, however those who persevere observe positive results in the long run.

Major aspects of sustainable agriculture

- **Agroecology: A holistic approach to farming**- agroecological practices are farming methods that are designed to produce considerable amounts of food while maintaining the balance between the crop production and ecosystem. Literature (Wezel et al., 2014) shows that rather than relying on conventional methods like chemical fertilizers, pesticides and other technological solutions like genetically modified organisms; agroecological practices aims to enhance the sustainability of agricultural sector by utilizing various

ecological services which include nutrient cycling by crop rotation, nitrogen fixation biologically, natural pest control methods, environmental conservation and biodiversity preservation. Crop rotation helps maintaining ecological and nutrient balance, where one crop helps to prepare the soil for future crops. These rotations improve soil composition by nutrient cycling and build up nutrient reserves to support the growth of subsequent crops. Literature (Wezel et al., 2014; Altieri, 1995; Altieri, 2018) reveals during the last few decades, the practices like using green manure, intercropping, cover crops, resource and biodiversity conservation practices have been more frequently referred to as agroecological practices.

- **Soil health** - Healthy and fertile soil works as a dynamic system which provides various services which enhance the productivity. It includes water retaining tendency, facilitating good sowing and growth of plant, regulating nutrient cycling by decomposition of biodegradable waste. Researches (Parr et al., 1992; Wezel et al., 2009; Vasu et al., 2020) show soil health is linked with sustainable agriculture as soil microorganism biodiversity are the key components of soil health. Recent activities like burning of stubble left in the farm after harvesting the crop has adverse effects on the soil as the organisms present in the soil became inactive and even destroyed. Food security is jeopardized by soil degradation occurring globally. Soil is also deteriorating as a result of activities on account of urbanization and industrialization. However improved soil quality has the potential and capacity to produce healthy and nutritious crops for sustainable food security worldwide.
- **Climate Resilience –** Climate change is directly linked with the production and management of crops. Any change in climate is associated with both natural and human activities. The crop which grows in a particular type of climate produces less yield if there is change in climatic conditions. Literature (El Chami et al., 2020; Srivastav et al. 2021; Tan et al., 2022) reveals that climate resilient strategies like developing climate change-resistant crops, improving irrigation techniques for proper water management, adopting smart agricultural practices can enhance food production and hence provide a route to food security. Technical training and scientific insights must be given to farmers so that they can handle the changing climatic parameters efficiently for sustainable agriculture.

All the above factors have crucial role to play in sustainable agriculture. By maintaining soil health, enhancing climate resilience and practicing agroecology, sustainable food system can be supported. In other words, by

relying less on external chemical inputs and following agroecological methods of crop production, burden on the soil can be reduced to a larger extent that can be associated with environmental degradation and often linked to climate change. Sustainable agriculture aims to consider all the above factors for environment friendly crop production without compromising the needs of future generation besides being ethical in the process.

Ethical framework for sustainable agriculture

Literature (Griswold, 1946; Kirschenmann, 2004) reveals the traditional approaches aiming for the ethical way of farming in agriculture sector that enables humans and other living being live decently on this green planet, Earth, while also preserving the spontaneous processes of the nature that support life like the one discussed by Thomas Jefferson. Another method involves the need of creating incentives to process change in the attitude and behaviour. Ethical food production ensures that human rights are respected throughout the food supply chain. This includes fair wages for workers in the agriculture sector, humane treatment of animals and all other living beings besides being ethical while in the process of crop production from sowing seeds to harvesting crops to marketing. Agricultural ethics ensures the healthy relationship between the human and nature for sustainable practices (Caporali & Caporali 2021). In this age of modernization, urbanization, globalization and climate change, the relationship between food demand, food production, food safety, food security, and food ethics defines the core of the agriculture sector in general and food system in particular. Agricultural ethics demand to examine the connections between these related areas, highlighting the connections and challenges that require to be addressed in a proper manner to address the issue of food security in a holistic and ethical approach. While food safety ensures public health, however sometimes unintentionally it undermines food security and ethical practices. Food insecurity often leads to ethical compromises which results in environmental degradation and exploitation of labour. Ethical shortcomings in food production sector threatens the sustainability, which therefore emphasizes the need for balanced approaches which takes care of ethical aspect. Ethical agriculture processes imagine the future where technology and traditional practices are combined keeping in view the ethical considerations for global food system (Balan et al., 2024). The outlook of an abundant, secure and ethically-driven food production system encourages us to switch to this approach to provide nourishment to the global population.

In India, various initiatives like National Mission on Sustainable Agriculture (NMSA), Paramparagat Krishi Vikas Yojana (PKVY), Rastriya Krishi Vikas Yojana (RKVY), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), the

Soil Health Card Scheme etc., are introduced by the government to foster sustainable agricultural practices in the country. Government policies in India play crucial role in ensuring food security of the nation without harming the the environment. Study (Tripathi et al., 2023) provides a review of few government schemes in India, emphasizing the objectives, implementation, and its impact in the progress of agriculture sector. Study (Tomar & Sharma, 2021) reports the effect of agriculture policies for sustainable agriculture ensuring food security besides revealing the impact of exploitation of natural resources, discussed considering few states of India. With the implementation of sustainable agricultural policies and schemes in a proper manner, socio-economic condition of the region can be improved besides ensuring food for all.

Organic farming practices for sustainable food production to ensure food security

Organic farming methods are the methods that works in harmony with the nature and avoid using chemicals, fertilizers, pesticides etc.. The interest in the organic farming due to its recognition as a sustainable agricultural system is increasing globally. Organic farming approach focuses to enhance physical, biological, and environmental resources, including soil nutrient content and microbial presence. Literature (Seufert et al. (2017); Willer et al., 2025) reveals organic farming constitutes less than 1% of agricultural land in the world, in spite of this it represents one of the rapidly expanding food sectors. Reports (Reddy, 2010; Seufert et al., 2017) show among the regions involved in organic farming; majority are from developing countries. In India also, a small percentage of area is under organic farming, though there is vast scope of organic farming here. India has a traditional background of practising organic agriculture but with industrialization and modernization, it had adopted chemical input-based methods to increase crop production however in recent years, due to awareness about the ill effects of fertilizers and pesticides, organic farming is promoted for sustainable healthy option for food security.

Although there exists significant debate regarding the profitability and increase in crop production in organic farming, yet there is broad agreement on its environmental benefits and its role in protecting human health. It often raises concerns about its practicality for feeding a growing global population, its financial and economic sustainability. However, numerous studies (Niggli, 2015; Reddy, 2010; Reganold & Wachter, 2016) suggest that organic agriculture can both be productive and sustainable. So there is need to boost the sector for global food security however currently, there is little government support or subsidies are available to make the transition to

organic farming which should be improved to make it more affordable or accessible.

Diverse benefits: the characteristics of organic agriculture

Organic agriculture aims at producing the food and raw materials while also addressing the ethical issues and is therefore offers a multi-functional agricultural concept.

Major benefits of organic farming leading to ecofriendly production of crops as reported in (Niggli, 2015; Haering et al., 2001; Hole et al., 2005) are:

- **Soil quality improvement**: Organic farming methods like crop rotation, natural nitrogen fixation, composting etc. helps in improving the soil texture, fertility, and microorganism growth.
- **Biodiversity protection**: Organic farming promotes the biodiversity by avoiding the use of chemical pesticides and fertilizers and by not burning the stubble left in the field after harvesting the crop.
- **Carbon Sequestration/ Carbon retention**: Organic farming practices use diversifying techniques like the crop rotations, reducing ploughing depth etc. which enhance the ability of soil to absorb and store carbon dioxide, which helps in decreasing climate change effects by reducing greenhouse gas emissions.
- **Efficient use of nitrogen fixed naturally:** Efficient use of nitrogen fixed naturally by growing crops (leguminous plants) which fix nitrogen naturally in rotation to other crops in agriculture helps to minimize excess fertilizer use, reducing the risk of nitrogen wash off and hence decreasing environmental damage. Researches show (Erisman et al., 2008) a small percentage of heavy soluble nitrogen fertilizer is taken up by the crops and the rest is lost to the environment in conventional farming whereas organic farming make efficient use of the available nitrogen.
- **Reducing harmful environmental impact**: Dependence on fertilizers and pesticides in conventional farming have adversely affected the environment however organic farming tend to reduce the impact by using ecofriendly techniques.
- **Protection of Water Resources**: Since organic farming avoids the use of harmful chemical fertilizers and pesticides, it reduces the chemical runoff into water systems thereby helps in preventing contamination of water sources, ensuring clean drinking water, preventing water pollution and protecting the various ecosystems.

These environmental benefits make organic agricultural practices a sustainable alternative to earlier farming methods. Additionally, the use of Artificial intelligence (AI) in organic farming in recent times is of great interest. Artificial intelligence (AI) in organic farming has the ability to revolutionize the agriculture sector. Research (Javaid et al., 2013; Kaur et al., 2024) indicates that AI technologies, such as crop monitoring, yield forecasting, and pest control, play a crucial role in boosting crop production and hence ensuring food security with intelligent application for sustainable agriculture for global food security.

Conclusion

Empowering farmers is essential to establish sustainable practices for food production to meet the needs of growing population worldwide. Farmers must be empowered through education, access to resources, improved market opportunities, science and technology etc.. Farmers can be equipped to face the challenges of the modern world. Farmers play a crucial role in addressing global food security. By empowering them, besides enhancement of their livelihoods, food security for other sections of the society is also secured. By minimizing chemical input dependencies and promoting ethical and organic ways of farming, food security can be achieved. Though it is difficult to give statements regarding food security worldwide however each step towards sustainable agriculture counts. Organic agriculture depends on environment friendly techniques of farming instead of relying on chemical inputs like fertilizers and pesticides that may have negative effects. Organic farming for sustainable agriculture blends traditional practices, innovation, and scientific knowledge to enhance the productivity for global food security.

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CHAPTER-17

CROP RESIDUE MANAGEMENT IN PADDY

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Abstract

The crop residue management has proved critical challenge and the unfavorable effects of residue burning on soil quality are at present major cause of concern. From past many years the practice of burning crop residue has resulted in concerns of public health and environmental degradation. Harvesting of different crops generates a large amount of residues mutually on the farm and off the farm. Large Quantity of crop residue is burnt on the farm in general for sowing of succeeding crop. Paddy stubble burning is predominant in the states of Punjab, Haryana and Uttar Pradesh. The problem of on the farm burning of crop residues is intensifying in recent years due to the high cost of removing the crop residue, high labor cost and mechanized system of harvesting the crops. In-situ crop residue management practices provide sustainability to maintain the fertility and health of the soil. Ex-situ crop residue management involves removal of agricultural waste from the field for various purposes such as compost making, power generation and animal feed etc.

Keywords: In-situ and Ex-situ crop residue management, Stubble burning.

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Introduction

India, the second largest agro-based economy with year-round crop cultivation, generates a large amount of agricultural waste, including crop residues. In the absence of adequate sustainable management practices, approximately 92 seems a very small number of metric tons of crop waste is burned every year in India, causing excessive particulate matter emissions and air pollution. Crop residue burning has become a major environmental problem causing health issues as well as contributing to global warming. Composting, biochar production and mechanization are a few effective sustainable techniques that can help to curtail the issue while retaining the nutrients present in the crop residue in the soil (Bhuvaneshwari et al., 2019). It is expected that in the order of 500-550 Mt of crop residues are produced per year in India. The crop residues are used for mulching, animal feeding, compost making, fuel for domestic and industrial use and use of thatches in rural areas. Thus crop residues are of great importance to the farmers. Instead of that a large portion of the crop residues is burnt on-farm keeping in view of to clear the field for sowing of the succeeding crop. The undesirable practice of on-farm burning of crop residues is intensifying in recent years. This is owing to many factors like shortage of human labor, the use of conventional methods of removing the crop residues of high cost, by and use of combines for harvesting of crops. Across different states of the country the residues of paddy, wheat, cotton, maize, sugarcane, jute, rapeseed-mustard, groundnut and millets are usually burnt on-farm. The conservation agriculture in the form of ex-situ and in-situ management of utilization of the crop residues in useful and profitable manner, conservation agriculture among the possible solutions. The conservation techniques can be used for improving soil health, increasing crop productivity, reducing pollution and enhancing sustainability of agriculture. The characteristic features of conservations techniques involving zero or minimum tillage, crop diversification, direct sowing and bed planting like innovative approaches in residues management (Bezboruah et al., 2024). As per available estimates, burning of crop residues is predominant in four states, namely, Haryana, Punjab, Uttar Pradesh & West Bengal consisting of top and leaves generate 12 Mt, i.e., 2% of the crop residues in India (Porichha et al., 2021).

Menace of crop residue burning:

Loss of nutrients: The crop residue is good source of carbon, nitrogen, phosphorous, potassium, and sulfur as 80% of Nitrogen (N), 25% of Phosphorus (P), 50% of Sulphur (S) and 20% of Potassium (K). Upon burning, these elements cause loss of nutrients as CO, CO_2, NO, Particulate matter and smoke (Reddy & Chhabra, 2022). It is expected that burning of

one tonne of rice straw accounts for loss of 5.5 kg Nitrogen, 2.3 kg phosphorus, 25 kg potassium and 1.2 kg sulphur besides, organic carbon. This also leads to air pollution and global warming. To enrich the soil with organic C and N the crop residue is to be incorporated or retained in the soil.

Adverse effect on soil health: The beneficial soil organisms killed due to the heat generated from burning residues which raise the soil temperature. Recurrent residue burning leads to complete loss of microbial population which is important for crop root development and reduces level of N and C in the top 0-15 cm soil profile. Reasonable crop residue input in a sustainable way is required to improve soil health and maintain the biological balance (Fu et al., 2021).

Release of greenhouse and other gases: The emission of Green House Gases (GHGs) and other chemically and radiative important trace gases and aerosols such as CH_4, CO, N_2O, NO_X and other hydrocarbons resulted due to the Crop residues burning. Due to the Crop residue burning it is estimated that Carbon (C) present in rice straw is emitted as CO_2 (70% of Carbon present), CO (7%) and CH_4 (0.66%) while 2.09% of Nitrogen (N) in straw is emitted as N_2O (Hayashi et al., 2014). Most of the pollutants found in large quantities in biomass smoke are known or suspected carcinogens and could lead to serious health hazardous resulted in air borne/lung diseases. The burning of crop residue also releases large amount of particulates are major source of Air pollution.

National Policy for Management of Crop Residue (NPMCR):

The present circumstances requires an appropriate policy package of technical and policy interventions for crop residues management is formulated for adoption by the States. In view of that, "National Policy for Management of Crop Residue (NPMCR)" has following major objectives:

a) Management of burning of crop residue to prevent environmental degradation and loss of soil nutrients and minerals by promotion of in-situ management (incorporation in soil, mulching, baling/binding for use as domestic/industrial fuel, fodder) of crop residue of different crops.

b) Diversified use of crop residue for various purposes like power generation, charcoal, gasification, , as industrial raw material for production of bio-ethanol, packing material, paper/board/panel industry, mushroom cultivation and composting etc.

c) Awareness about ill effects of crop residue burning and capacity building and its effective utilization and management, Formulation and implementation of suitable legislative/policy and law.

d) Measures to restrain burning of crop residue (Porichha et al., 2021).

The Policy having other thrust area comprises:

a) Endorsement of technologies for optimum utilization and in-situ management of crop residue to prevent loss of precious soil nutrients, minerals and soil health management.

b) Adoption of diversified uses of crop residue for various purposes viz. power generation, as industrial raw material for production of bioethanol, packing material for glassware, fruits & vegetables and utilization for paper/ board/panel industry, biogas generation/composting and mushroom cultivation in the mode of Public Private Partnership (PPP).

c) Involvement in capacity building programmes of various stakeholders including farmers and extension functionaries under crop development programmes and organization of field level demonstrations on management of crop residues in all programmes/schemes;

d) Mechanization and development of machineries for effective utilization of such residues including promotion of adaptive research for management of crop residue.

e) Formulation and execution of necessary policy measures for control of crop residue burning through suitable laws/ legislation/ executive orders etc. Interventions to restrain crop residue burning: Various interventions to curb crop residue burning are listed below for adoption (Porichha et al., 2021).

Technological interventions:

a) To maintain the soil moisture and to check the soil erosion the crop residue is incorporated into the soil following conservation techniques.

b) Preparation of bio-compost/vermicompost and its utilization in various crops with the use of crop residue.

c) The utilization of crop residue for cultivation of mushroom particularly *Agaricus bisporus* (white button mushroom) and *Volvariella Volvacea* (straw mushroom).

d) Motivation for purchase of happy seeder/ turbo seeder / shredder/ baling machines and zero- seed-cum-fertilizer drill with incentives to facilitate in-situ management of crop residue and retaining the straw as surface mulching.

e) Subsidy Extension to the farmers for hiring resource conservation machineries from Custom Hiring Center/Agriculture Service Center and promotion of establishment of new CHC/ASC to ensure availability of such machines to the farmers at the time of crop harvesting.

Multiple uses of crop residue:

a) Diversified use of crop residue as fuel for power plants, production of cellulosic ethanol, etc. in Public Private Partnership (PPP) for promotion of various interventions under ongoing schemes/programmes.

b) Encouragement for use of crop residue/rice straw in paper/board/panel and packing material.

c) Endorsement of collection of crop residue for feed, brick making, etc.

d) Extending subsidy for transport of crop residue to fodder deficient areas.

Capacity building and awareness generation:

a) Training of farmers organized for creating awareness about effects of crop residue burning, adoption of conservation agriculture practices and resource conservation technology through all ongoing State/Centre Sector Schemes.

b) Prevention of crop residue burning through mass media, print media, etc. just before the harvesting seasons by creating of awareness about various measures.

c) Establishing self-help groups and providing subsidy to unemployed youth for establishment of custom hiring centres to enhance the availability of resource conservation machinery.

d) Self certification by farmers to not resort to crop residue burning need to further certified by Gram Pradhan/ Sarpanchas as an additional condition while availing crop loan/agricultural credit from financial institutions.

e) Demonstrations of crop residue management technology on a large scale by the State Department of Agriculture and other Government Institutions by organising on-farm demonstrations to create awareness and dissemination of various technologies and organising field days under ongoing programmes/schemes.

Pilot studies on management of crop residue:

a) Cost effective farm machinery for farmers to be developed to facilitate collection, volume reduction, transportation and application of crop residues.

b) To get chopped crop residues, combine harvester modified to collect finely by use of twin cutter bar type combine harvester for harvesting of top portion of crop for grain recovery and a lower cutter bar for straw harvesting at a suitable height and windrowing should be developed for proper straw management.

c) To monitor crop residue management use of satellite based remote sensing technologies, with active involvement of National Remote Sensing Agency (NRSA) and CPCB of MoEF & CC.

Laws and legislation to control crop residue burning:

a) It is for the State Governments to take necessary steps to curb the practice of crop residue burning keeping in view of as per Seventh Schedule of the Constitution of India, subject of agriculture falls under the purview of the State Governments, accordingly, States, namely; Andhra Pradesh, Bihar, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Tamil Nadu and Uttar Pradesh should bring suitable law/rules/order for prevention/banning of the practice of crop residue burning as per policy and priority of the State. Accordingly, State Government may identify an agency or authority to implement such an order to subside, prevent and ban the practice of crop residue burning.

b) Incentivizing establishment of projects aiming at utilization of crop residues as raw materials by entitling them to all benefits as permissible under the Fiscal Incentives for Industrial Promotion schemes/programmes in the respective State; and

c) Ministry of Environment, Forests & Climate Change (MoEF&CC) may issue an advisory to various State Governments and Union Territories to control this trouble of crop residue burning.

Financial resource mobilization for management of crop residue:

1. Fund mobilization of management of crop residues involves a multidisciplinary approach and therefore, fund mobilization for this purpose has to come from various Ministries, such as MoEF&CC, MoA, MoRD, etc. MoA (DAC) provides financial support to State Governments through various on-going schemes/ programmes for the interventions required to control crop residue burning. For example, Governments of Haryana and Punjab have proposed under Annual Work Plan of Rashtriya Krishi Vikas Yozna for seeking central assistance for providing machineries (happy seeder/turbo seeder/shredder/ baling machines & zero-seed-cum-fertilizer drill) to the farmers to facilitate in-situ management of crop residue and retaining the straw as su mulching for crops. State Governments & supplementary ministries may also take up similar steps to control practice of crop residue burning.

2. Development and implementation of Annual Work Plan (AWP) of various ongoing schemes/programmes/missions of DAC State Governments may identify various need based, location specific interventions suitable to

particular agro-ecological zones for management of crop residues. Moreover, State can also avail financial assistance from Rashtriya Krishi Vikas Yojana (RKVY), which provides flexibility to the states for taking up any components/interventions required for management of crop residue in a holistic manner and integrated development of agriculture.

Monitoring Mechanism:

1.It is mainly for State Governments to identify various interventions, formulate a suitable work plan, and monitor its implementation by multidisciplinary team of Officers.

2. To control the practice of burning of crop residue at national level, the issue of management of crop residue will be monitored at regular intervals especially before each crop harvesting season to ensure effective implementation of proactive measures.

In Situ Crop Residue Management

The stubble burning on extreme increases the risk of acute respiratory problems threefold, subject to exposure (Chakrabati et al., 2019). In the Delhi National Capital Region and surrounding areas atmospheric modeling studies estimated that during the peak burning, stubble burning contributes up to 30 per cent of post-harvest PM 2.5 levels (Lohan et al., 2018; Bedi et al., 2024). Keeping in view of the health impacts of stubble burning, states such as Punjab have adopted several measures, including the promotion of short-duration paddy varieties to extend the stubble management window, subsidies for CRM machines, and financial incentives for industries to create a market for biomass (PAU, 2013). The two most major CRM machines one is the existing stock of Super Seeders (43,452 units) and other is the Happy Seeders (13,560 units) is sufficient to cover 100 per cent of the paddy fields in Punjab if deployed at maximum capacity. The lower adoption rate of zero-burn residue management due to the factors like barriers to timely access to CRM machines and their inflated operational charges, coupled with misperceptions over reduced yields and pest attacks on wheat sown using in-situ CRM machines (Kurinji & Prakash, 2021; Parihar et al., 2023).

Of the 754 Mt of crop biomass produced annually, nearly 228 Mt remain as surplus after being utilised for processes such as roof thatching and cattle bedding; the majority of it is burnt.The practice of burning is prominent in northern states such as Punjab, where rice–wheat farming dominates. Factors contributing to this longstanding practice include the paddy–wheat cropping system, cultivation of long-duration paddy varieties, mechanised harvesting that leaves standing crop stubble in the field, labour scarcity and the lack of a viable market for crop residue (Kurinji & Prakash, 2021).

Nearly 77 per cent of farmers following in-situ methods reported maintaining traditional sowing practices without making the recommended changes. Among them, over 20 per cent who experienced a decline in wheat yield and pest attacks attributed these issues to the use of in-situ CRM machines. Incorporating the prescribed changes in the application of irrigation, fertilisers, and rodent control measures while using in-situ machines can mitigate concerns surrounding the decline in wheat productivity and pest attacks. Further, only 7 per cent of farmers practising in-situ methods had received any training in using CRM machines.

Ex-situ CRM is gaining momentum

• The adoption of ex-situ CRM, such as using stubble for fodder or energy production, is gaining popularity due to its potential for additional income. According to our survey, nearly 33 per cent of the surveyed farmers opted for ex-situ methods, and 66 per cent of these farmers had formerly employed in-situ methods to manage their stubble. This indicates a clear preference for ex-situ over in-situ options, as costs associated with in-situ methods continue to be a burden for farmers.

• Ex-situ methods include providing residue to biomass aggregators/balers (60.4 per cent of ex-situ users), followed by supplying it to pastoral communities for fodder (28.8 per cent) and nearby industries.

• However, farmers adopting ex-situ methods are not entirely satisfied. A meagre 3 per cent of ex-situ farmers received payments of about INR 1,200 per acre when selling the paddy stubble. Moreover, while nearly 28 per cent had to pay the buyer to clear the stubble, 69 per cent gave the stubble away free of cost.

In view of our findings, we recommend that all policy actors in Punjab and beyond focus on the following measures to reduce crop residue burning in the coming seasons.

Paddy varietal diversification

• Despite the ban on the cultivation of PUSA 44 by the Punjab government in October 2023, its seeds are still in circulation through private seed dealers. The state must enforce strict inspections of private seed dealers, distributors and producers to ensure a complete phase out of the variety.

• The last two sowing seasons (2022 and 2023) involved a rapid depletion of seed stock for popular varieties such as PR 126 and PR 128. Many farmers had to resort to less popular varieties such as PR 121. Therefore, state authorities must encourage recognised institutions such as the Indian Council of Agricultural Research (ICAR), agricultural universities, government seed

farms, the National Seed Corporation and state seed agencies to undertake large-scale seed breeding and retention of popular PR varieties to meet the state's seed demand.

• The initiative to procure summer moong at the minimum support price (MSP) if the farmers sowed PR 126 or basmati in the same field after harvesting moong in 2022 triggered massive demand for PR 126 seeds among farmers (Qasim, 2012 & Kamal, 2022). The state must continue such incentives to promote the adoption of short-duration varieties among PUSA-growing farmers.

In-situ CRM methods

• The state has been introducing new crop residue management machines annually under its CRM subsidy scheme – Super Seeders in 2020, Smart Seeders in 2022, and Surface Seeders in 2023. While Super Seeders are commonly preferred, machines such as Happy Seeders, Smart Seeders, and Super SMS have limited acceptance among farmers. To avoid incorrect resource allocation, it is imperative to assess the efficacy of these machines and farmers' preferences in terms of cost and yield through pilot programmes before incorporating them into the subsidy scheme. To this end, the state must codify an evaluation framework to include only machines with demonstrated success in the crop residue management subsidy scheme.

• The Punjab government has ambitious targets to scale the rental model of crop residue management machines through its i-Khet app. But the app in its current version collects extensive personal data, including Aadhaar numbers and land ownership information, making it less attractive among farmers. To resolve this, the Punjab Remote Sensing Centre (PRSC) must upgrade the app to incorporate responsive design and cater to farmers' needs, preferences, and behaviours. Further, it must enable the automatic alert feature to send personalised notifications covering the health and cost benefits of crop residue management techniques, improvement in soil health, agricultural cost effective inputs.

Punjab is an agricultural state with wheat and rice as major crops. The wheat straw is used as fodder by the animal, whereas, the use of paddy straw is limited. Paddy was cultivated in 31.67 lakh hectare area (2022) in Punjab resulting in generation of about 20.08 million tons of paddy straw. The details of area under paddy sown in the State of Punjab during Kharif season viz-a-viz paddy straw generation are as in table 1 & 2:

Table 1: Showing Area under cultivation and paddy straw generation in year 2021, 2022 and 2023

Year	Area under Paddy (Lac ha)	Area under Non-Basmati (Lac ha)	Area under Basmati (Lac ha)	Paddy Straw Generation (Million Ton)		
				From Area under Non-Basmati @ 6.5 T / ha	From Area under Basmati @ 5.5 T / ha	Total Paddy Straw Generation
2021	29.61	24.72	4.89	16.07	2.69	18.74
2022	31.67	26.73	4.94	17.37	2.71	20.08
2023 (Est.)	31.00	25.00	6.00	16.25	3.30	19.55

Table 2: Paddy Residue Utilization by various strategy

Sr. No.	Strategy	Paddy Residue Utilization Target (Mt)			
		2020-21	2021-22	2022-23	2023-24
1.	Crop Diversification	2.57	3.57	4.57	5.22
2.	In-situ CRM	6.45	8.13	9.44	10.70
3.	Ex-situ CRM	0.92	1.22	1.52	4.67
	Total	**9.94**	**12.92**	**15.53**	**20.59**

Source: Government of Punjab (2022a)(MoAFW, 2022a);Government of Punjab (2022b) (MoAFW, 2022a)

Conclusion

The ex-situ crop residue management practice is highly acceptable among farmers as it provides additional income and does not necessitate altering the crop production process whereas the ex-situ sector is slowly growing in Punjab, only 2.9 per cent of the 33 per cent of farmers following ex-situ methods received payments of about INR 1,200 per acre while selling their stubble. The remaining farmers either gave the stubble free of cost or paid around INR 1,000 per acre to clear the stubble. Farmers adopted for long duration for long duration variety due to high yields, limited use of crop residue management machines, limited uptake of rental models to access crop residue management machines. The adoption of in-situ and ex-situ methods has become common among farmers in recent years, accessibility, affordability, and cost-effectiveness are still significant determinants to

replacing conventional burning. Even among farmers following the in-situ method, nearly half followed partial burning in Kharif 2022 to ensure the smooth operation of crop residue management machines. Punjab has a long way to go in becoming a zero-stubble-burning state, better use of existing techniques and targeted outreach can accelerate its voyage in the forthcoming futuristic practices.

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CHAPTER-18

ECO-DRIVEN PACKAGING: A NEW ERA OF ENVIRONMENTAL STEWARDSHIP

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Abstract

Packaging is one of the fastest-growing industries across the globe and expanding day by day. This growth is primarily driven by factors like growing Pharmaceutical, Food Processing, Manufacturing Industry and FMCG sector. In India, packaging industry which is the 5th largest sector of India's economy is developing at the rate of 22-25% per annum and becoming a preferred hub for packaging industry. The Indian Packaging Market was valued at US $ 50.5 billion in 2019 and is expected to reach US $ 204.81 billion by 2025. In 2019, India produced around 17 million tons of plastic, out of this approx. 59% was used in packaging, of which only 15% was effectively recycled with the rest either incinerated or dumped in landfill. Product packaging is a critical component of the consumer experience, but it also represents a significant source of waste and environmental impact. From single-use plastics to excessive packaging, traditional methods are increasingly viewed as unsustainable. As a result, there is a growing demand for innovative packaging solutions that minimize environmental harm while maintaining functionality and aesthetic appeal. Therefore, the packaging industry is witnessing a wave of innovation and has been undergoing a major transformation towards sustainability and technological advancements for

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eco-friendly solutions. This growth is fuelled by consumer awareness about the environmental impact of plastic packaging and government initiatives to promote sustainable practices. The objective of the current paper is to examine innovations in the Eco-Friendly Packing and shifting of pharmaceutical industry, E-commerce industry and Food and Beverage industry towards sustainable packaging strategies in response to environmental concerns and the Government initiatives to promote sustainable packing solutions.

Keywords: Packaging industry, Pharmaceutical Industry, E-commerce industry, Food and Beverage industry, Sustainability.

Introduction

The packaging industry plays a critical role in the global economy. It focuses on designing, manufacturing, and distributing packaging materials for wide range of products including food and beverages, pharmaceuticals, cosmetics, and other consumer goods etc. The global packaging industry is developing and expanding day by day. The overall global packaging production in 2020 reached 3.8 trillion units, and a further 2.3% annual growth rate was forecasted until the year 2025, with a significant growth expected in Asia and Africa(Ncube et al., 2021). The main estimated growth sectors will be soft drinks, dairy and confectionery. Furthermore, the COVID-19 pandemic influenced the packaging sector, increased the demand for packaging protecting against contamination and leading to a significant growth of packaging for the food delivery market and for the e-commerce. The Indian Packaging industry is also growing at the same pace (Gurtu& Arendt, 2020). This growth is primarily driven by factors like growing pharmaceutical, food processing, manufacturing industry, FMCG, healthcare sector and ancillary in the economies across the globe (Soares, 2010).The Indian Packaging Market was valued at US$ 50.5 billion in 2019, and it is estimated at US$ 204.81 billion in 2025, and is expected to reach US $ 39.13 billion by 2031, at a CAGR of 11.46% during the forecast period (2025-2031) (Gurtu& Arendt, 2020; Ibrahim et al., 2022). Packaging industry is among the high growth industries in India which is developing @ 22-25% per annum. Currently, the 5th largest sector of India's economy, the industry has reported steady growth over past several years and shows high potential for much expansion, particularly in the export market(Kozik, 2020; Ncube et al., 2021).

Objectives of the Paper

To study the growth of Packaging Industry since Prehistoric to present times.

To examine shifting of pharmaceutical industry, E-commerce Industry and Food and Beverage industry towards sustainable packaging to address environmental concerns.

To study initiatives at the global level and role of Government of India to promote sustainable packing.

Growth of Packaging Industry

The history and growth of the packaging industry is quite engrossing, as it indicates how manlike society and technology have evolved over time. During Prehistoric to Ancient Times, humans used natural materials like leaves, bark, animal skins, and clay containers to pack food, water, and other necessities. Ancient civilizations like the Egyptians, Greeks, and Romans developed their own methods of packaging using clay pots, glass, and metal containers to store goods. With the Industrial Revolution in the 18th and 19th centuries, the packaging industry began to see large changes. Paper and cardboard became widely used for packaging during this time, as they were inexpensive, easy to produce, and could be used for various types of products. The invention of furrowed cardboard in 1871 was a breakthrough for packaging, especially for shipping goods. Glass Bottles also became popular during this era for packaging beverages, medicines, and perfumes. The development of tin canning revolutionized food storage and preservation during early 20th century. It led to the global expansion of food products, allowing them to be shipped and stored for longer periods. The creation of the first synthetic plastic, Bakelite, in 1907 marked the beginning of plastic's role in packaging(Baekeland, 2002). Mid-20th Century was the era of Convenience Packing and Consumerism. Packaged goods, especially in single-serve portions, became widespread. This era also witnessed the popularization of brands and the introduction of colourful, eye-catching packaging designs that catered to a growing middle-class market(Baekeland, 2002; Baker, 2018). 1960-1970 was the period of Plastic Revolution. The development of polyethylene and polypropylene opened the door for flexible packaging options like plastic bottles, bags, and shrink wraps. Packaging became lighter, cheaper, and more versatile. Cartons were also introduced during 1960s especially those used for liquids. Introduction of Tetra packs for beverages revolutionized the way liquids were packaged and transported. During the latter part of the 20th century**,** growing apprehensions regarding pollution and waste sparked the initial dialogues surrounding sustainability in packaging. It was during this period that the advocacy for recycling, minimizing packaging waste, and the emergence of environmentally conscious materials began to take form. With the rise of digital printing and

RFID technology, packaging began to embrace high-tech solutions during 1990 to 2000 (Bibi et al., 2015; Shen et al., 2019). Companies used these technologies for better inventory management, product tracking, and even enhancing customer engagement through smart packaging. 21st Century, the current era, is witnessing a significant shift towards Sustainability and Technological Integration in the packaging industry. The global emphasis on sustainability has revolutionized the packaging sector. Biodegradable materials, plant-based plastics, and zero-waste packaging have gained substantial traction(Davis & Song, 2006). Consumers are increasingly advocating for more environmentally conscious options, prompting companies to embrace recyclable, reusable, or compostable materials(Shaikh et al., 2021; Siracusa et al., 2008).

Environmental and Health Concerns

The packaging industry, while essential for modern commerce and consumer goods, also significantly contributes to various environmental challenges. The extensive use of plastic in packaging is a matter of grave concern. The Indian packaging sector consumes a substantial portion of the nation's plastic, with 42% utilized in flexible packaging and 17% in rigid packaging. In India, approximately 17 million tons of plastic are produced annually, of which around 59% is allocated for packaging purposes, with only 15% effectively recycled, while the remainder is either incinerated or deposited in landfills (UNEP, 2021**).** The consumption of plastic in packaging in India surpasses the global average trend, accounting for roughly 59% of the total consumption of 19.8 million tonnes in 2020 (Hossain et al., 2023)**.**

Conventional packaging materials have a significant adverse impact on the environment due to their composition of non-renewable resources such as metals and plastics, as illustrated by alarming statistics provided in the diagram above. The extraction, production, and disposal of these materials result in the generation of large amounts of waste, the release of pollution into the environment, and deforestation. Plastic has emerged as a symbol of environmental disaster, with 3.4 million tonnes being produced daily in India alone. Single-use plastics not only contaminate water bodies and pose a threat to wildlife but also require millennia to degrade.

A major issue lies in the widespread usage of single-use plastic packaging. Items like bottles, wrappers, and straws contribute significantly to plastic waste, which often finds its way into landfills, rivers, oceans, and various ecosystems. Plastic packaging, particularly in the form of microplastics, poses a severe threat to marine and human life. Marine creatures frequently ingest

plastic waste, resulting in harm, mortality, and the disruption of marine ecosystems(Ghosh et al., 2023). Plastics can take centuries to decompose, leading to enduring environmental harm if not appropriately recycled or disposed of. Plastic packaging used in the food and beverage industry poses a significant threat to human health as plastics contain toxic substances that can leach into consumables. Prolonged exposure to these chemicals may pose health hazards, such as hormone disruption or cancer. A study by Leblanc et al. (2021) emphasizes that plastic packaging, in particular, has a considerable environmental impact due to its low recycling rates. An estimated 8 million tons of plastic waste end up in the oceans annually, causing harm to marine organisms.

The manufacturing of packaging materials such as plastic, paper, and glass depletes natural resources. The extraction of fossil fuels for plastic production, metal mining, and deforestation for paper packaging all contribute to resource exhaustion. For instance, the production of plastic and glass entails substantial energy inputs, resulting in carbon emissions and climate change. The production, transportation, and disposal of packaging materials generate greenhouse gas emissions, primarily through the use of fossil fuels in manufacturing processes and logistics. From raw material extraction to disposal, packaging often leaves a significant carbon footprint(Mak et al., 2022; Ncube et al., 2021).

Numerous products are excessively packaged with multiple layers of materials (e.g., plastic, foil, cardboard). This over-packaging leads to unwarranted waste generation. For instance, electronics are often composed of diverse materials that are challenging to separate and recycle, contributing to e-waste and landfill overflow. A major challenge lies in the complexity of packaging materials, which frequently consist of multiple layers that are not easily separable for recycling(Asante et al., 2019; Kozik, 2020)**.**

Paper-based packaging materials, though deemed more sustainable than plastic, still contribute to deforestation, particularly when sourced unsustainably. Trees are felled for paper pulp, diminishing biodiversity and escalating carbon emissions(Bertolini et al., 2016; Mak et al., 2022). This negatively impacts ecosystems and wildlife, potentially leading to habitat loss and contributing to global warming. Life cycle assessments (LCAs) conducted by Finkbeiner et al. (2019) reveal that the energy required to manufacture packaging materials like aluminum and PET (Polyethylene Terephthalate) is substantial, contributing to greenhouse gas emissions. Paper-based packaging, although generally considered environmentally friendly, also necessitates significant resources in terms of water and energy during production, according to Thompson et al. (2020).

Certain packaging materials utilize synthetic dyes, inks, and coatings containing harmful chemicals such as phthalates, bisphenol A (BPA), and other endocrine-disrupting substances. These chemicals can contaminate water sources and harm wildlife if not disposed of properly. With the rise in packaging waste volume, landfills are rapidly filling up at an unsustainable rate. Finding new landfill space, particularly in urban areas, is becoming increasingly challenging(Marchiandi et al., 2024).

Sustainable Packaging Trends by Different Industries

The packaging industry has been undergoing a major transformation, driven by sustainability concerns, technological advancements, and consumer demand for eco-friendly solutions. Companies are exploring new materials, like biodegradable plastics and plant-based alternatives, to reduce environmental impact. Recyclability is becoming a top priority as well, with packaging designed to be easily reused or repurposed.

Pharmaceutical Industry

The Pharmaceutical Industry recognizes the significant role of packaging beyond just protecting products and is now transitioning towards sustainable packaging solutions to address environmental concerns and meet the increasing demand for pharmaceutical goods. The industry is adopting biodegradable materials such as Polylactic Acid (PLA) and Polyhydroxyalkanoates (PHA), which are sourced from plants, as alternatives to conventional plastic and metal packaging. These materials decompose naturally, contributing to a reduction in environmental impact and waste buildup (Z. Naser et al., 2021).

Glaxo SmithKline (GSK) has made significant commitments to improving the sustainability of its packaging. One such initiative involves the use of recycled PET (rPET) in its packaging for products like over-the-counter medicines. The company has also set a target to use 100% recyclable or reusable packaging for all its consumer healthcare products by 2025.Johnson & Johnson has made efforts to reduce plastic packaging in its products. The company has committed to eliminating 50% of plastic in its product packaging by 2030, with an emphasis on using biodegradable materials and making packaging more recyclable. Bayer, another leading pharmaceutical company, is also focusing on reducing plastic waste. In certain product lines, Bayer has already switched from plastic to paper-based materials for packaging. For example, their over-the-counter medications like aspirin are increasingly being sold in eco-friendly cardboard packaging rather than plastic bottles. Companies are adopting minimalist packaging designs that use

fewer materials but still ensure the product's safety and efficacy. For Example: Roche has worked to optimize its packaging by reducing the volume of packaging material. The company has designed some of its pharmaceutical products to be packaged in smaller, more compact cartons to minimize the environmental footprint while maintaining the integrity of the product.

Pfizer is investing in packaging solutions that reduce waste across both primary and secondary packaging. It has introduced blister packs made from recyclable materials for some of its medications.

Commerce Industry

The shift towards sustainable packaging in e-commerce is not only driven by consumer demand for greener practices but also by increasing regulations and environmental awareness. These solutions, which include using recycled materials, biodegradable packaging, and even reusable systems, have been adopted by several brands.

Examples of Sustainable Packaging Solutions

- **Amazon** uses 100% recycled content in cardboard packaging. Amazon, in particular, has successfully reduced the usage of single-use plastic by 97,222 metric tons in 2021 through the implementation of eco-friendly paper alternatives and reusable packaging designs.
- **Flipkart** has achieved a milestone of 100 percent elimination of plastic packaging and adoption of sustainable packaging alternatives across the supply chain.At Flipkart, the sustainable packaging program has been developed taking into account the end-to-end process behind shipping the product from one warehouse to another and ultimately to the customer's doorstep.
- **Patagonia** utilizes recycled plastic, such as recycled PET, in its product packaging.
- **Lush i**mplements compostable and biodegradable materials for its packaging.
- **Ecovative** offers mushroom-based packaging as an alternative to Styrofoam or plastic peanuts.
- **Apple** is adopting minimalist designs to reduce excess packaging. It is focusing on sustainable and compact packaging solutions to minimize waste.

- Some businesses are incorporating reusable packaging options like returnable packaging and tote bags. Returnity partners with brands like Rothy's and Pela Case to provide reusable shipping bags for future shipments.
- **Plant-Based Packaging:** E-commerce companies are exploring plant-based materials also such as cornstarch, bamboo, and sugarcane waste as alternatives to plastic. Ikea and HP have already started using plant-based materials in their products and packaging.
- **Paper Alternatives:** Some companies are opting for FSC-certified paper as a sustainable alternative for packaging materials.

Food and Beverages Industry

The Food and beverage industry is shifting towards sustainable packaging practices to address environmental concerns and meet consumer demand. This includes reducing waste, lowering carbon footprints, and using eco-friendly materials.

Major companies like Coca-Cola, PepsiCo, and Nestlé are taking steps to make their packaging more sustainable by incorporating recycled materials and setting ambitious goals for recyclability by specific deadlines. In 2020, the Coca-Cola announced a goal to make 100% of its packaging recyclable globally by 2025 and to use 50% recycled content in its PET plastic bottles by 2030 (Bumbudsanpharoke& Ko, 2019). PepsiCo has also committed to using 100% recycled content in its plastic packaging by 2030. In 2021, PepsiCo launched a new Frito-Lay snack bag made from 100% recycled plastic, marking a step toward reducing the environmental impact of its snack packaging. Nestlé's Water brands in certain markets are moving to bottles made entirely from recycled plastic (rPET), while other products are made with packaging that contains 50% or more recycled material. The company has set ambitious targets to make 100% of its packaging recyclable or reusable by 2025. Companies are exploring innovative solutions such as edible packaging, with examples like Loliware creating edible cups and straws from seaweed-based materials. Initiatives like Loop, partnering with brands like Nestlé and Procter & Gamble, are introducing a zero-waste, reusable packaging system to reduce environmental impact. Starbucks has implemented "borrow-a-cup" programs to encourage the use of reusable cups, decreasing the reliance on disposable cups and lids.

Packaging made from renewable plant-based materials like corn, bamboo, or sugarcane is becoming increasingly popular as a sustainable alternative to traditional plastic packaging. Anheuser-Busch InBev and McDonald's are examples of companies investing in innovative sustainable packaging solutions such as barley-based packaging and FSC-certified paper to reduce reliance on petroleum-based plastics and ensure recyclability, compostability, or biodegradability by specific targets.

Government Initiatives for Sustainable Packaging in India

Governments play a pivotal role in advancing sustainable packaging through a combination of regulations, incentives, and public awareness campaigns. By promoting the utilization of recyclable, reusable, and biodegradable materials, as well as incentivizing businesses to minimize packaging waste, these initiatives are paving the way for a more sustainable future (Ramanathan et al., 2023). The European Union has assumed a leadership position in tackling these issues, with initiatives such as Single Use Plastics Directive; the Circular Economy Action Plan striving to enhance the sustainability of packaging. Legislative measures like the Plastic Packaging Tax in the UK which applies to plastic packaging containing less than 30% recycled content and prohibitions on single-use plastics in various nations underscore the escalating regulatory pressure on the packaging industry to embrace more sustainable practices (Pani & Pathak, 2021). The Indian government has implemented policies and programs such as the Plastic Waste Management Rules 2016 to advocate for sustainable packaging. These regulations stipulate the usage of compostable plastics and promote the adoption of recyclable materials. Efforts like the Swachh Bharat Abhiyan concentrate on waste management and environmental sustainability, endorsing investments in sustainable packaging (Pani & Pathak, 2021).

- **Plastic Waste Management Rules (PWM), 2016:** Introduced by the Ministry of Environment, Forest and Climate Change (MoEFCC) to reduce plastic waste and promote recycling. Mandates Extended Producer Responsibility (EPR) for producers, importers, and brand owners, with specific targets set for waste collection, segregation, and recycling.
- **Plastic Waste Management (Amendment) Rules, 2018:** Amended regulations aim to phase out non-recyclable multi-layered plastic (MLP) packaging within two years. Promotes the use of recyclable alternatives to reduce plastic waste.

- **Single-Use Plastics (SUP) Ban:** Various States and Union Territories in India have implemented bans on single-use plastics like bags, cutlery, and straws to combat plastic pollution. Maharashtra, for instance, enforced a ban in June 2018.
- **National Packaging Policy (NPP):** Currently under consideration by the Indian government to tackle packaging waste issues and encourage sustainable practices. Aims to establish standards, promote recycling, and facilitate the use of eco-friendly packaging materials.
- **Eco-Mark Certification Scheme:** Implemented by the Bureau of Indian Standards (BIS) to certify environmentally friendly products, including packaging materials. Products meeting specified criteria for environmental performance and sustainability are eligible for certification.

Initiatives at the Global Level

Numerous global endeavors are propelling the embrace of sustainable packaging solutions by diminishing waste, enhancing recyclability, and advocating for biodegradable or reusable materials. Below are some pivotal initiatives:

1. International Agreements & Policies

UN Sustainable Development Goals (SDGs) – Particularly Goal 12 (Responsible Consumption and Production) and Goal 14 (Life Below Water) concentrate on reducing packaging waste and plastic pollution.

Basel Convention (Plastic Waste Amendments) – Reinforces international regulations on plastic waste trade to mitigate environmental repercussions.

European Union Green Deal & Circular Economy Action Plan – Enforces legislations such as the Packaging and Packaging Waste Directive (PPWD) to ensure all packaging in the EU is reusable or recyclable by 2030.

Global Plastics Treaty (Under UNEP) – Ongoing deliberations to establish a legally binding treaty to eradicate plastic pollution.

2. Corporate & Industry-Led Initiatives

The Ellen MacArthur Foundation's New Plastics Economy – Encourages enterprises to pledge to a circular economy model for plastic packaging by stressing on packaging reuse, recycling and reducing waste generation.

Consumer Goods Forum (CGF) Plastic Waste Coalition – A worldwide coalition of corporations like Nestlé, Unilever, and P&G striving to eradicate problematic plastics and amplify sustainable alternatives.

The Sustainable Packaging Coalition (SPC) – A North American venture that advocates for environmentally friendly packaging through design innovations and material exploration(Pani & Pathak, 2021).

Reusable Packaging Association (RPA) – Concentrates on endorsing reusable packaging solutions across various sectors(Klemeš, 2012).

3. Certifications & Standards

Forest Stewardship Council (FSC) – Certifies sustainable paper and cardboard packaging.

Cradle to Cradle (C2C) Certification – Guarantees packaging materials are safe, circular, and responsibly sourced.

OK Compost & TUV Austria Certifications – Authenticate biodegradable and compostable packaging solutions.

ISO 18604 – International benchmark for packaging and the environment.

4. Technological & Material Innovations

Biodegradable & Compostable Materials – Progressions in plant-based plastics (PLA, PHA), seaweed-based packaging, and edible packaging.

Recyclable Mono-Materials – Singular polymer plastics engineered for simplified recycling.

Smart and Connected Packaging –

(a)Utilizing QR codes and NFC tags : providing consumers with detailed product information, traceability and interactive experiences through smartphones.

(b)Temperature and Freshness Sensors: Packaging integrated with sensors will monitor food freshness and detect spoilage.

(c) Blockchain for Tranparency:Improved tracking of products from manufacturing to delivery.

(d) Personalisation and Customisation: AI powered designs to create personalised packaging experiences. Through Digital Printing Technology, businesses can produce small batches of customized packaging efficiently on demand.

Deposit Return System (DRS): incentivize consumers to return plastic bottlesand cans for recycling. Countries like Norway and Germany have highly effective DRS programmes.

5. Consumer & Retailer Initiatives

Plastic-Free Aisles & Refill Stations – Supermarkets in Europe and Asia are launching sections devoid of plastic and refill schemes.

Extended Producer Responsibility (EPR) Programs – Mandating enterprises to assume accountability for their packaging waste.

Zero-Waste Movements – Encouraging patrons to utilize reusable bags, bottles, and containers.

Support for Research and Innovation: Governments fund research into alternative packaging materials like bioplastics, edible packaging and plant - based materials. Collaborations with Universities and businesses are encouraged to develop sustainable packaging technologies.

Union Budget 2025-26 Vis-A-Vis Packaging Industry

The Union Budget for the fiscal year 2025-26, unveiled on February 1, 2025, has introduced a series of measures that will have a substantial impact on the packaging industry in India. Notable highlights include:

1. **Advocacy for Sustainable Packaging:** The government has earmarked funds to champion sustainable packaging solutions. This encompasses tax incentives for environmentally friendly materials, subsidies, and interest rate reductions for state-of-the-art recycling facilities. Moreover, the Goods and Services Tax (GST) on recycling machinery and the processing costs of recycled granules have been slashed from 18% to 5%, with the aim of promoting recycling practices(Pani & Pathak, 2021).

2. **Production-Linked Incentive (PLI) Scheme for Biodegradable Alternatives:** A PLI scheme has been introduced to stimulate the production of biodegradable packaging materials. This initiative is anticipated to attract investments and cultivate innovation in sustainable packaging technologies(Ramanathan et al., 2023).

3. **Technical Upgradation Fund**: The announcement of a technical upgradation fund for the plastic processing sector has been made, with an allocation of ₹2,500 crore over a span of five years. This fund is designed to bolster the sector's competitiveness and encourage the adoption of cutting-edge technologies(Bumbudsanpharoke& Ko, 2019).

4. **GST Reductions:** The GST on plastic waste and recycling machinery has been reduced to zero, while the GST on the conversion cost of recycled plastic granules has been diminished from 18% to 5%. These measures are crafted to incentivize recycling efforts and alleviate the financial burden on manufacturers.

5. **Plug-and-Play Facilities for MSMEs:** The proposal to establish plug-and-play facilities aims to offer fully equipped infrastructure for Micro, Small, and Medium Enterprises (MSMEs) in the packaging sector. This initiative seeks to alleviate the financial strain on smaller businesses and facilitate smooth operations.

These endeavors underscore the government's unwavering commitment to nurturing a sustainable and competitive packaging industry in India.

The Union Budget 2025 has garnered favorable reception from leaders in the packaging industry, who have widely praised its focus on manufacturing, MSME support, and sustainability. While the sector welcomes initiatives that stimulate consumer spending and industrial growth, experts concur that additional incentives for eco-friendly materials, recycling infrastructure, and R&D in sustainable packaging would have further expedited the industry's transition towards environmental consciousness. As the budget sets the stage for a more resilient and competitive economy, the packaging sector remains steadfast in its commitment to driving innovation and sustainability in India.

Jeevaraj Pillai**,** the director of sustainability and president of flexible packaging and new product development at UFlex, has acknowledged the budget's favorable stance towards augmenting disposable income through revised tax slabs. He posits that this will catalyze increased consumption of FMCG products, consequently driving up the demand for packaging solutions.

"We commend the government's emphasis on bolstering disposable income, which is poised to infuse more liquidity into the market. This strategic move is anticipated to bolster the consumption of packaged goods, setting off a chain reaction that would benefit the packaging industry. Nevertheless, further support in critical areas such as tax incentives for eco-friendly materials, subsidies for recycling facilities, and more robust incentives for Extended Producer Responsibility (EPR) compliance could have accelerated the sector's shift towards sustainability," remarked Pillai.

Conclusion

The future of sustainable packaging looks promising, with continued growth expected in the coming years. As consumer awareness and government

regulations continue to drive the demand for sustainable packaging solutions, the industry is likely to witness further innovations and advancements. The industry will continue to evolve with biodegradable materials**,** recycled content, minimalist designs, and circular economy models driving the transition toward a more sustainable future. As consumer demand for eco-friendly packaging grows and governments introduce stricter regulations, the packaging industry will become increasingly focused on sustainability, creating a future where packaging no longer contributes to the waste problem but instead plays a role in a more circular, environmentally responsible economy. By embracing eco-friendly packaging, businesses in India can contribute to a cleaner environment and position themselves for long-term success in an increasingly sustainable market. Future of packaging in every sector will likely see more innovation and collaboration between governments, businesses, and consumers to create more sustainable packaging solutions while ensuring the safety and efficacy of the products.

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CHAPTER-19

SUSTAINABLE PREPAREDNESS FOR ROGUE WAVE IMPACTS

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Abstract

An elusive understanding of oceanic rogue waves has recently started to unfold with the development of certain theoretical models and it was shown that they could produce certain solution like structures under highly nonlinear conditions. Search waves are essentially surface gravity waves but with a height of more than 20 metres. The most recent developments in the theoretical understanding come from the second order random wave theory and it's probabilistic approach. Given the fact that these waves carry immense amount of energy that far exceeds the design capacity of structures such as ships and platforms/rigs. Study explores the existing models that have been developed in understanding surface waves that result in Rogue rave phenomenon. The most recent consensus on this regard has reached a point where the models are able to predict rock waves do not give a clear physical understanding as to what natural mechanisms come together in practice. Although rare in occurrence but still wreak havoc to any human or man-made structure it encounters. Some commonly reported encounters that happened to give significant towards the understanding of rogue waves have also been discussed.

Keywords: Ocean, Wave, Rogue Wave, Sustainable.

Introduction

Physical phenomena have been long stated to represent reality and physical systems that are contained within it. Essentially the properties of matter and energy and their interaction with each other constitute the nature of physical

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systems as well as is the basis of the scientific study. The overarching goal is to come up with a unifying set of laws that are able to explain multiple phenomena using a unified set of rules(Davies, 1992). This study is one such example where equations found for the use of quantum mechanics and the probability distribution of wave functions has also found an application in the study of ocean waves and their propagation(Cattrell et al., 2018).

Among other things the natural environment today is affected by a multitude of factors both natural as well as man-made. The phenomenon of ocean rogue waves or freak waves or monster waves what is the subject of tell-tale stories of sailors for the longest time, they were reported by sailors but there was no conclusive evidence and most importantly it was very difficult to find an experiment that would consistently repeat this phenomenon(Guo, 2010). However, in the late 1960's and 70s, visual sightings as well as advanced censors give information about the existence of extremely high waves moving in a solitary fashion against the ocean. Eventually more evidence gathered, and it was found out that general fluid mechanics was insufficient required consideration of non linear phenomena generation of such waves.

Sightings and measurement of rogue waves

It is now understood that the conditions that come together to create a Rogue Wave are very rare and therefore sightings were not accepted by standard science for a long time. However, in the New Year's Day in 1995 something important happened that changed the outlook as well as research towards surface and oceanic waves. 160 kilometres away from Norway pause the newly constructed dropper platform. It was state of the art and was equipped with several sensors for oceanic and sea wave measurement on the mentioned day the sensors recorded away that was 26 metres high. Given that as per generally accepted theories a wave should not be more than 6 metres high, this news made headlines in the scientific community. For the longest time it was very difficult for people to believe this but now they had to accept it because the evidence was right in front of them. At the same time this prompted people to figure out new theories that explained such phenomena because the classical wave theories did not account for search high waves under any condition. This wave was aptly called as Draupner wave and has been subject of a lot of research ever since.

This all changed with the construction of a new kind of oil rig in 1994, 160 kilometres (100 miles) off the coast of Norway. The Draupner platform(Cavaleri et al., 2017) was the first of its kind, and for precautionary purposes for passengers, modernized equipment for monitoring of frequency and wave height sensors were fitted on board. In the night of January 1, 1995, these sensors recorded what should not have been possible: A wave, from

trough to crest, 26 meters (85 ft) high—higher than any recording taken by those sensors since the last 48 hours. It was also more than 6 meters (20 ft) higher than the theoretical calculation for highest possible water wave. Scientists also believed that such an occurrence was so rare that it would be seen once in ten millennia (Walker et al., 2004). While the oil rig wasn't majorly damaged by the wave due to its height, minor damage to the underside of the platform confirmed the validity of the reading. This made the Draupner Wave, as it was later named, the first confirmed measurement of a rogue wave, which meant science finally had to acknowledge their existence.

To quote from history, during the World War 2, in 1943 the RMS *Queen Mary*, carrying over 15,000 soldiers, was broadsided by a 28-meter (90-foot) wave(*RMS Queen Mary - Infogalactic: The Planetary Knowledge Core*, n.d.). The force of the impact caused the ship to heel dramatically, reaching a list of 52 degrees within seconds. Sailors on board were alarmed because that ship was twice the size of the famous RMS *Titanic*. Remarkably, however, the *Queen Mary* managed to recover and return to an upright position, averting what could have been one of the most devastating maritime disasters in history. Unfortunately, the phenomenon of rogue waves would not be studied for at least half a century later and therefore no explanation was found at the time. When a vessel is struck laterally by a rogue wave, the combination of the ship's extensive surface area and the wave's immense energy can induce catastrophic rolling, potentially leading to capsizing. Had the ship been slightly smaller or tilted a few additional degrees, it would almost certainly have capsized, killing 15000 lives without a trace.

There were other sightings at different times and when the theory of Rogue waves became it was understood that a lot of ships that were lost in history were not exactly lootings or destruction but could also be a single solitary Rogue Wave that happened to hit an unlucky ship. In December 1978, the freighter Marion reported receiving SOS signals from a cargo ship M S München (Manzetti, 2023). The ship was crossing the North Atlantic and it was going through a fierce storm although there was no initial cause to worry. However, an hour after receiving the SOS signal the ship was nowhere to be found. After an intensive search operation, it was found that the ship was hit by a wave 30 metre high and had been broken into pieces simply by the shear kinetic energy of the water. Even with its modern design the ship was not designed to handle behaves higher than 15 to 20 metres. Also, it was noted that the ship was hit by single wave only, rather than a series of recurring hits. The international community was shocked and any doubts about the existing theories of rogue waves had been conclusively resolved. Rogue waves exist! And now there is theory as well as evidence behind it.

This was further supported by other incident recorded about a year later when the large portion liner Queen Elizabeth 2 was hit by a wave 27 meter

tall(Lichtenstein, 2016). This is comparable to a height of a 9-story building. Incidentally this happened in broad daylight and was visually observed by many people including the captain of the ship who allegedly reported that he had never seen anything like that in his service career. A comparable incident occurred in 2001 involving the cruise ship *Bremen*, which encountered a 35-meter (115-foot) rogue wave. The wave struck the vessel head-on, causing significant damage to the bridge and disabling its engines. For approximately 30 minutes, the ship drifted uncontrollably through the storm. The crew eventually managed to activate a backup engine, regaining partial control of the vessel and averting further disaster.

The mysterious disappearances of the MS München and numerous other ships, both before and after this tragic event, were often attributed to technical failures, design flaws, or human mistakes. However, the possibility that some of these vessels might have been struck by rogue a wave was rarely considered by the scientific community, even as late as the 20th century.

Rogue waves

Rogue Wave is a solitary wave that has been generated as a result of several superposition coming together leading to an abnormally large wave height (amplitude). This means that waves traveling at different speeds or directions can superpose, leading to a large amplitude short lived wave (Dysthe et al., 2008). Since wave height is a very complicated function dependent on characteristics of water atmosphere as well as other geophysical and electromagnetic forces at play, determining exactly what the amplitude of typical wave might be is far easier than it sounds. Waves traveling at different speeds or directions can pile up, creating a constructive interference (a single huge wave for a short period of time). It has been studied and several factors result in such phenomena, such as constantly changing wind speeds and direction, surface and tidal waves, or the topological details of the ocean floor. As mentioned, general linear models describe wave heights as high as 6 metres, and even until the late 20th century there were no mathematical models that could describe waves as high as 20 or more(Forristall, 2005). Today the most important description of a Rogue Wave through its height is that these waves have a height of more than 20 metres, and most importantly occur in a solitary fashion.

Another defining characteristic of rogue waves is their unusual “steepness”. In contrast to ordinary ocean waves that generally exhibit a gradual rise and fall (and thus enabling vessels to navigate them safely, even during severe storms), rogue waves possess a disproportionately short wavelength relative to their height. This unique structural attribute results in extraordinarily steep wave fronts. Consequently, rogue waves manifest as *‘near-vertical walls of*

water', capable of striking objects in their trajectory with immense force, leaving them virtually unstoppable and highly destructive(Dudley et al., 2019).

It is important to be clear about distinction between rogue waves and tsunamis, as the two phenomena are fundamentally distinct in their origins as well as characteristics. Tsunamis are characterized by a *series of waves* that propagate through the entire water surface(Akhmediev et al., 2009), typically generated by subsurface and sea-bed level seismic activity. These typically come in the form of tectonic movements and earthquakes or undersea volcanic eruptions. Due to their extensive wavelengths (often spanning hundreds of kilometers), tsunamis displace vast volumes of water. However, in the open ocean, their long wavelengths and low wave heights make them virtually undetectable to vessels. It is only upon reaching coastal regions where the ocean floor rises. Here the waves are forced to compress and decelerate(Kharif et al., 2008).This throws the water to devastating heights, often reaching 10, 20, or even 30 meters. In contrast, rogue waves are a product of nonlinear interactions among typical ocean waves and are confined to the surface level activity(Gupta et al.,2023). These waves emerge spontaneously in the open ocean. Characterized by their transient nature, they dissipate almost as rapidly as they form. Unlike tsunamis, rogue waves do not pose a significant threat to coastal areas, as their steep and unstable structure causes them to break down in shallow waters. However, in deep oceanic regions, rogue waves represent a severe hazard to maritime navigation. They have been shown to inflict catastrophic damage and even sinking large, modern vessels. Their sudden and unpredictable formation has troubled researchers for many years are these are open questions even today(Dysthe et al., 2008; Kharif et al., 2008, Gupta et al.,2023).

The most significant hazard posed by rogue waves lies in the extraordinary and sudden release of kinetic energy. These forces far exceed the design standards of modern shipbuilding. For example, a wave height of 3-meter generates a braking pressure of approximately $1.5\ mT/m^2$ (metric tons per square meter).To compare, in general stormy conditions, a 12-meter storm wave can produce pressures of around $6\ mT/m^2$. Ships and marine vessels are designed to withstand breaking forces of up to $15\ mT/m^2$. Now, rogue waves reaching heights of 30 meters can exert pressures ranging from 75 to $100\ mT/m^2$, with some estimates suggesting peak forces as high as 500 mT/m^2. It should come as no surprise given the numbers about the kind of damage these waves create(Kharif et al., 2008).

These incidents highlight the urgent as well as careful need for improvements in maritime engineering, safety policies and protocols for the safety of personnel and property.

Impact of rogue waves

Rogue waves have been shown to pose a significant risk to ships, infrastructure and human life. These massive waves can capsize or sink vessels, leading to loss of property. Additionally, crew members and passengers may sustain injuries, ranging from minor wounds to severe trauma, due to direct impact or violent vessel shaking(Wisner et al., 2014). The operational integrity of ships is almost always compromised. Apart from ships, coastal infrastructure such as docks and piers suffer extensive damage. Ports, seawalls, and offshore oil and gas platforms are left useless and lead to billions of dollars in repairs(Bramwell et al., 2021; Vozzo et al., 2021). These accounts highlight the economy and logistical consequences of these unpredictable oceanic events.

Rogue waves can have profound and far-reaching impacts on both biodiversity and the physical environment. Consequences vary depending on the wave's magnitude and location. Ecologically, these waves can devastate marine ecosystems by damaging coral reefs, coastal habitats like marshes and mangroves. They displace or eradicating populations of vulnerable species such as sea turtles and marine mammals. Such disruptions are directly responsible for loss of biodiversity, as many species struggle to adapt to the altered conditions(Vozzo et al., 2021; Witt et al., 2012). They also contribute to coastal erosion, resulting in the loss of critical beach and dune habitats, as well as property and infrastructure along shorelines. Additionally, rogue waves can trigger environmental disasters, such as oil spills or the release of hazardous materials, when they damage ships or offshore installations.

Mitigation and prevention measures

With a better understanding of the underlying mechanisms and the impact that has been caused by the rogue waves we are now in a position to utilise our understanding and come up with solutions. The last 2 decades have seen significant changes in policies and design principles search that any incident is properly recorded as well as marine structures that are strong enough to withstand such forces. Impact of kinetic energy and its destructive consequence has led to Peter design of ships and offshore ocean platforms. Similar to tsunami prevention, the use of buoys has been implemented which alarm local areas of any incoming rogue wave(Akhmediev, Ankiewicz, et al., 2011; Akhmediev, Soto-Crespo, et al., 2011).

One notable region where rogue waves frequently occur is off the coast of South Africa. In this area, the waves come from the southern Atlantic and go to northeast towards the “Agulhas Current”. This is a powerful opposing current that brings warm water from the Indian Ocean down towards Atlantic

and Antarctic(Ohta & Yang, 2012). This interaction causes wave energy to concentrate, leading to waves that become significantly steeper and with short wavelength. This phenomenon results in formation of rogue waves and to make matters worse, it lies on a very busy shipping lane from India to Europe.

Extensive wave data collected from a onsite oil and gas rig situated in the South Indian Ocean (also known as the Agulhas Current) further showed that the extreme nature of rogue waves was something worth being careful of. Over a 6-year period from 1998 to 2003, sensors recorded more than 1500 instances of waves more than 12 m, meeting the criteria for rogue waves(Cevik & Miryugin, 2022). Notably, the data also documented over a dozen occurrences of waves measuring 4 to 10 times the significant wave height, with some reaching staggering heights of 30, 40, and nearly 50 meters (160 feet). This is equivalent to the height of a 16-story building!

These findings have led to increased alarm and awareness among merchant and maritime forces. Ships routes are mapped to avoid the Agulhas Current. Emergencies are broadcast during extreme weather conditions. Suchmitigation steps are very necessary for encountering rogue waves. But even then, this precaution does not eliminate the danger entirely. A substantial number of rogue waves appear to form unpredictably in the open ocean. These seemingly random occurrences cannot be fully explained by conventional wave dynamics. It continues to pose a significant challenge to maritime safety and scientific understanding.

Conclusion

This article discusses the mechanisms of generation and the impact of rogue waves as has been recorded over the recent history. We started off with a very limited understanding of search phenomena and within half a century and even less we are now table to find the underlying equations and reasonably understand how these waves are generated. However, it is still an open question to completely and deterministically predict search phenomenon. This is where the interdisciplinary nature of quantum physics and its strange properties come into the picture. Quantum physics shows that superposition of various wave components can interact and exchange energy between them without any evident cause. Although this is rare but very much within the realm of possibility. These interactions produce unstable behaviour and allow the wave to travel over short periods of time but with immense bursts of energy. To quote simply, rogue waves are generated through nonlinear superposition of multiple interacting energy components at the ocean surface.

Preliminary studies on phenomena of rogue waves had shown that it would take approximately 24,000 years for such of phenomena to occur at least on a probability basis. However, this assumption was completely debunked and

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CHAPTER-19

SUSTAINABLE PREPAREDNESS FOR ROGUE WAVE IMPACTS

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Abstract

An elusive understanding of oceanic rogue waves has recently started to unfold with the development of certain theoretical models and it was shown that they could produce certain solution like structures under highly nonlinear conditions. Search waves are essentially surface gravity waves but with a height of more than 20 metres. The most recent developments in the theoretical understanding come from the second order random wave theory and it's probabilistic approach. Given the fact that these waves carry immense amount of energy that far exceeds the design capacity of structures such as ships and platforms/rigs. Study explores the existing models that have been developed in understanding surface waves that result in Rogue rave phenomenon. The most recent consensus on this regard has reached a point where the models are able to predict rock waves do not give a clear physical understanding as to what natural mechanisms come together in practice. Although rare in occurrence but still wreak havoc to any human or man-made structure it encounters. Some commonly reported encounters that happened to give significant towards the understanding of rogue waves have also been discussed.

Keywords: Ocean, Wave, Rogue Wave, Sustainable.

Introduction

Physical phenomena have been long stated to represent reality and physical systems that are contained within it. Essentially the properties of matter and energy and their interaction with each other constitute the nature of physical

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systems as well as is the basis of the scientific study. The overarching goal is to come up with a unifying set of laws that are able to explain multiple phenomena using a unified set of rules(Davies, 1992). This study is one such example where equations found for the use of quantum mechanics and the probability distribution of wave functions has also found an application in the study of ocean waves and their propagation(Cattrell et al., 2018).

Among other things the natural environment today is affected by a multitude of factors both natural as well as man-made. The phenomenon of ocean rogue waves or freak waves or monster waves what is the subject of tell-tale stories of sailors for the longest time, they were reported by sailors but there was no conclusive evidence and most importantly it was very difficult to find an experiment that would consistently repeat this phenomenon(Guo, 2010). However, in the late 1960's and 70s, visual sightings as well as advanced censors give information about the existence of extremely high waves moving in a solitary fashion against the ocean. Eventually more evidence gathered, and it was found out that general fluid mechanics was insufficient required consideration of non linear phenomena generation of such waves.

Sightings and measurement of rogue waves

It is now understood that the conditions that come together to create a Rogue Wave are very rare and therefore sightings were not accepted by standard science for a long time. However, in the New Year's Day in 1995 something important happened that changed the outlook as well as research towards surface and oceanic waves. 160 kilometres away from Norway pause the newly constructed dropper platform. It was state of the art and was equipped with several sensors for oceanic and sea wave measurement on the mentioned day the sensors recorded away that was 26 metres high. Given that as per generally accepted theories a wave should not be more than 6 metres high, this news made headlines in the scientific community. For the longest time it was very difficult for people to believe this but now they had to accept it because the evidence was right in front of them. At the same time this prompted people to figure out new theories that explained such phenomena because the classical wave theories did not account for search high waves under any condition. This wave was aptly called as Draupner wave and has been subject of a lot of research ever since.

This all changed with the construction of a new kind of oil rig in 1994, 160 kilometres (100 miles) off the coast of Norway. The Draupner platform(Cavaleri et al., 2017) was the first of its kind, and for precautionary purposes for passengers, modernized equipment for monitoring of frequency and wave height sensors were fitted on board. In the night of January 1, 1995, these sensors recorded what should not have been possible: A wave, from

trough to crest, 26 meters (85 ft) high—higher than any recording taken by those sensors since the last 48 hours. It was also more than 6 meters (20 ft) higher than the theoretical calculation for highest possible water wave. Scientists also believed that such an occurrence was so rare that it would be seen once in ten millennia (Walker et al., 2004). While the oil rig wasn't majorly damaged by the wave due to its height, minor damage to the underside of the platform confirmed the validity of the reading. This made the Draupner Wave, as it was later named, the first confirmed measurement of a rogue wave, which meant science finally had to acknowledge their existence.

To quote from history, during the World War 2, in 1943 the RMS *Queen Mary*, carrying over 15,000 soldiers, was broadsided by a 28-meter (90-foot) wave(*RMS Queen Mary - Infogalactic: The Planetary Knowledge Core*, n.d.). The force of the impact caused the ship to heel dramatically, reaching a list of 52 degrees within seconds. Sailors on board were alarmed because that ship was twice the size of the famous RMS *Titanic*. Remarkably, however, the *Queen Mary* managed to recover and return to an upright position, averting what could have been one of the most devastating maritime disasters in history. Unfortunately, the phenomenon of rogue waves would not be studied for at least half a century later and therefore no explanation was found at the time. When a vessel is struck laterally by a rogue wave, the combination of the ship's extensive surface area and the wave's immense energy can induce catastrophic rolling, potentially leading to capsizing. Had the ship been slightly smaller or tilted a few additional degrees, it would almost certainly have capsized, killing 15000 lives without a trace.

There were other sightings at different times and when the theory of Rogue waves became it was understood that a lot of ships that were lost in history were not exactly lootings or destruction but could also be a single solitary Rogue Wave that happened to hit an unlucky ship. In December 1978, the freighter Marion reported receiving SOS signals from a cargo ship M S München (Manzetti, 2023). The ship was crossing the North Atlantic and it was going through a fierce storm although there was no initial cause to worry. However, an hour after receiving the SOS signal the ship was nowhere to be found. After an intensive search operation, it was found that the ship was hit by a wave 30 metre high and had been broken into pieces simply by the shear kinetic energy of the water. Even with its modern design the ship was not designed to handle behaves higher than 15 to 20 metres. Also, it was noted that the ship was hit by single wave only, rather than a series of recurring hits. The international community was shocked and any doubts about the existing theories of rogue waves had been conclusively resolved. Rogue waves exist! And now there is theory as well as evidence behind it.

This was further supported by other incident recorded about a year later when the large portion liner Queen Elizabeth 2 was hit by a wave 27 meter

tall(Lichtenstein, 2016). This is comparable to a height of a 9-story building. Incidentally this happened in broad daylight and was visually observed by many people including the captain of the ship who allegedly reported that he had never seen anything like that in his service career. A comparable incident occurred in 2001 involving the cruise ship *Bremen*, which encountered a 35-meter (115-foot) rogue wave. The wave struck the vessel head-on, causing significant damage to the bridge and disabling its engines. For approximately 30 minutes, the ship drifted uncontrollably through the storm. The crew eventually managed to activate a backup engine, regaining partial control of the vessel and averting further disaster.

The mysterious disappearances of the MS München and numerous other ships, both before and after this tragic event, were often attributed to technical failures, design flaws, or human mistakes. However, the possibility that some of these vessels might have been struck by rogue a wave was rarely considered by the scientific community, even as late as the 20th century.

Rogue waves

Rogue Wave is a solitary wave that has been generated as a result of several superposition coming together leading to an abnormally large wave height (amplitude). This means that waves traveling at different speeds or directions can superpose, leading to a large amplitude short lived wave (Dysthe et al., 2008). Since wave height is a very complicated function dependent on characteristics of water atmosphere as well as other geophysical and electromagnetic forces at play, determining exactly what the amplitude of typical wave might be is far easier than it sounds. Waves traveling at different speeds or directions can pile up, creating a constructive interference (a single huge wave for a short period of time). It has been studied and several factors result in such phenomena, such as constantly changing wind speeds and direction, surface and tidal waves, or the topological details of the ocean floor. As mentioned, general linear models describe wave heights as high as 6 metres, and even until the late 20th century there were no mathematical models that could describe waves as high as 20 or more(Forristall, 2005). Today the most important description of a Rogue Wave through its height is that these waves have a height of more than 20 metres, and most importantly occur in a solitary fashion.

Another defining characteristic of rogue waves is their unusual “steepness”. In contrast to ordinary ocean waves that generally exhibit a gradual rise and fall (and thus enabling vessels to navigate them safely, even during severe storms), rogue waves possess a disproportionately short wavelength relative to their height. This unique structural attribute results in extraordinarily steep wave fronts. Consequently, rogue waves manifest as *‘near-vertical walls of*

water', capable of striking objects in their trajectory with immense force, leaving them virtually unstoppable and highly destructive(Dudley et al., 2019).

It is important to be clear about distinction between rogue waves and tsunamis, as the two phenomena are fundamentally distinct in their origins as well as characteristics. Tsunamis are characterized by a *series of waves* that propagate through the entire water surface(Akhmediev et al., 2009), typically generated by subsurface and sea-bed level seismic activity. These typically come in the form of tectonic movements and earthquakes or undersea volcanic eruptions. Due to their extensive wavelengths (often spanning hundreds of kilometers), tsunamis displace vast volumes of water. However, in the open ocean, their long wavelengths and low wave heights make them virtually undetectable to vessels. It is only upon reaching coastal regions where the ocean floor rises. Here the waves are forced to compress and decelerate(Kharif et al., 2008).This throws the water to devastating heights, often reaching 10, 20, or even 30 meters. In contrast, rogue waves are a product of nonlinear interactions among typical ocean waves and are confined to the surface level activity(Gupta et al.,2023). These waves emerge spontaneously in the open ocean. Characterized by their transient nature, they dissipate almost as rapidly as they form. Unlike tsunamis, rogue waves do not pose a significant threat to coastal areas, as their steep and unstable structure causes them to break down in shallow waters. However, in deep oceanic regions, rogue waves represent a severe hazard to maritime navigation. They have been shown to inflict catastrophic damage and even sinking large, modern vessels. Their sudden and unpredictable formation has troubled researchers for many years are these are open questions even today(Dysthe et al., 2008; Kharif et al., 2008, Gupta et al.,2023).

The most significant hazard posed by rogue waves lies in the extraordinary and sudden release of kinetic energy. These forces far exceed the design standards of modern shipbuilding. For example, a wave height of 3-meter generates a braking pressure of approximately $1.5\ mT/m^2$ (metric tons per square meter).To compare, in general stormy conditions, a 12-meter storm wave can produce pressures of around $6\ mT/m^2$. Ships and marine vessels are designed to withstand breaking forces of up to $15\ mT/m^2$. Now, rogue waves reaching heights of 30 meters can exert pressures ranging from 75 to $100\ mT/m^2$, with some estimates suggesting peak forces as high as 500 mT/m^2. It should come as no surprise given the numbers about the kind of damage these waves create(Kharif et al., 2008).

These incidents highlight the urgent as well as careful need for improvements in maritime engineering, safety policies and protocols for the safety of personnel and property.

Impact of rogue waves

Rogue waves have been shown to pose a significant risk to ships, infrastructure and human life. These massive waves can capsize or sink vessels, leading to loss of property. Additionally, crew members and passengers may sustain injuries, ranging from minor wounds to severe trauma, due to direct impact or violent vessel shaking(Wisner et al., 2014). The operational integrity of ships is almost always compromised. Apart from ships, coastal infrastructure such as docks and piers suffer extensive damage. Ports, seawalls, and offshore oil and gas platforms are left useless and lead to billions of dollars in repairs(Bramwell et al., 2021; Vozzo et al., 2021). These accounts highlight the economy and logistical consequences of these unpredictable oceanic events.

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