ISBN: 978-93-48620-51-4

ENVIRONMENTAL SUSTAINABILITY: EMERGING PERSPECTIVES AND PRACTICES

VOLUME II

Editors:
Dr. K. Maruliya Begam
Ms. K. Safana Yasmin

Bhumi Publishing, India
First Edition: November 2025

Environmental Sustainability: Emerging Perspectives and Practices

Volume II

(ISBN: 978-93-48620-51-4)

DOI: https://doi.org/10.5281/zenodo.17865009

Editors

Dr. K. Maruliya Begam

Department of Electrical and Electronics Engineering,

Periyar Maniammai Institute of Science and Technology,

Vallam-613 403, Thanjavur, Tamilnadu

Ms. K. Safana Yasmin

Department of Information Technology,

V.S.B. Engineering College,

Karur-63 9111, Tamilnadu

Bhumi Publishing

November 2025

Title: Environmental Sustainability: Emerging Perspectives and Practices Volume II

Editors: Dr. K. Maruliya Begam, Ms. K. Safana Yasmin

First Edition: November 2025

ISBN: 978-93-48620-51-4

DOI: https://doi.org/10.5281/zenodo.17865009

Published by Bhumi Publishing,

a publishing unit of Bhumi Gramin Vikas Sanstha

Bhumi Publishing

Nigave Khalasa, Tal – Karveer, Dist – Kolhapur, Maharashtra, INDIA 416 207

E-mail: bhumipublishing@gmail.com

Disclaimer: The views expressed in the book are of the authors and not necessarily of the publisher and editors. Authors themselves are responsible for any kind of plagiarism found in their chapters and any related issues found with the book.

PREFACE

Environmental sustainability has become one of the most defining challenges of the twenty-first century. Rapid industrialization, urban expansion, climate instability, resource depletion, and biodiversity loss continue to reshape ecosystems and influence the socio-economic trajectory of nations. Against this backdrop, the book "Environmental Sustainability: Emerging Perspectives and Practices" seeks to provide a comprehensive overview of contemporary environmental concerns while offering fresh and innovative approaches to address them.

This volume brings together contributions from diverse researchers, academicians, practitioners, and environmental thinkers. Each chapter explores critical themes such as sustainable resource management, green technologies, environmental policy, circular economy, climate change mitigation, ecosystem restoration, and community-based conservation. Collectively, these perspectives highlight not only the urgency of environmental protection but also the opportunities for transforming current practices into more resilient and regenerative systems.

A key objective of this book is to bridge the gap between theoretical concepts and real-world applications. The authors offer case studies, best practices, and emerging models that showcase how sustainability can be integrated into agriculture, industry, urban planning, waste management, and renewable energy initiatives. By presenting multiple viewpoints, the book encourages readers to think holistically and adopt interdisciplinary solutions.

Environmental sustainability is no longer a subject confined to ecological research; it has evolved into a multidisciplinary framework involving science, technology, economics, sociology, and governance. We hope that the insights compiled in this volume will serve as a valuable resource for students, teachers, researchers, policymakers, environmental managers, and anyone committed to building a greener and more equitable future.

We express our sincere gratitude to all contributors for their scholarly efforts and to everyone who supported the publication of this volume. It is our belief that this book will inspire meaningful action and contribute to ongoing dialogue about sustainable development, environmental ethics, and ecological responsibility.

- Editors

TABLE OF CONTENT

Sr. No.	Book Chapter and Author(s)	Page No.
1.	**CONSEQUENCES OF LIVESTOCK SECTOR CARBON FOOTPRINTS: IMPLICATIONS FOR SUSTAINABILITY** Sivachandiran R, Sundar A, Vijaya Bharathi M and Elango A	1 – 6
2.	**SUSTAINABLE ENERGY EFFICIENT AND ECONOMICAL INDUSTRIAL FACILITY DESIGN** Vivekanand Shere, Hiraman Jadhav, Yogesh Shirke and Prashant Titare	7 – 16
3.	**SMART AC CHARGING MANAGEMENT SYSTEM FOR ELECTRIC VEHICLES** R. Elavarasi, S. Murugesan, S. Selva Kumar, S. Aravindan and S. Vishwas	17 – 26
4.	**CLIMATE-RELATED HEALTH ISSUES: HEAT, AIR QUALITY, AND PHYSIOTHERAPY MANAGEMENT** Sanhita Sengupta and Sonia Gupta	27 – 38
5.	**PHYTOREMEDIATION AN ECO-FRIENDLY TOOL FOR WASTE WATER MANAGEMENT** Seema Bhagowati	39 – 47
6.	**STATISTICAL ASSESSMENT OF GROUNDWATER QUALITY USING HYDRO-CHEMICAL PARAMETERS FOR DRINKING WATER IN DEOLA, SATANA, AND MALEGAON TEHSILS IN NASHIK, MAHARASHTRA** Chetan Ashokrao Patil, Pravin Mukund Nalawade, Kailas Devaram Ahire, Bharat Laxman Gadakh, Nutan Vijay Khangar and Ashish Vilas Mane	48 – 59
7.	**ROLE OF FUNGI IN BIOREMEDIATION OF TEXTILE DYES** Pravin V. Gadakh	60 – 70
8.	**COMPREHENSIVE REVIEW OF VERMICOMPOSTING: MECHANISMS, APPLICATIONS, AND ENVIRONMENTAL IMPACTS IN SUSTAINABLE WASTE MANAGEMENT AND SOIL REMEDIATION** Santhi Ramalingam and Krishnakumar M	71 – 86

9.	**AGROFORESTRY: ECO-FRIENDLY SOLUTIONS IN ADDRESSING AND ADJUSTING TO CLIMATE CHANGE** Kaberi Mahanta, Seema Bhagowati, Kusum Kumar Deka and Samiran Pathak	87 – 100
10.	**MULTI-STRANDED PIEZOELECTRIC ENERGY HARVESTING FOR VEHICULAR APPLICATIONS** Prabhu Raddy, Rutuja Deshmukh, Sagar Bhavsar and Prashant Dike	101 – 108
11.	**A STATISTICAL STUDY OF CLIMATE CHANGE IN NASHIK DISTRICT** Nutan V. Khangar and Kalpesh P. Amrutkar	109 – 123

CONSEQUENCES OF LIVESTOCK SECTOR CARBON FOOTPRINTS: IMPLICATIONS FOR SUSTAINABILITY

Sivachandiran R*, Sundar A, Vijaya Bharathi M and Elango A
Department of Veterinary Public Health and Epidemiology,
Veterinary College and Research Institute, Salem – 636 112
*Corresponding author Email: scrvet2019@gmail.com

Abstract:
The animal sector is both a contributor to and a victim of climate change, with its carbon footprint driving wide-ranging biological, economic and environmental consequences. Greenhouse gases from enteric fermentation, manure management, feed production and land-use change intensify global warming, while rising temperatures, heat stress and shifting disease patterns threaten animal health, productivity and welfare. These impacts translate into reduced yields, higher mortality, increased veterinary costs and economic instability for producers, particularly smallholders. Climate-driven disruptions in feed availability, trade flows and food supply chains further heighten food security risks. At the same time, a suite of mitigation strategies including enteric methane inhibitors, improved manure handling, climate-smart feeding, silvopastoral systems and integrated policies, offers viable pathways to reduce emissions while enhancing resilience. This chapter synthesizes current evidence on the livestock sector's carbon footprint, its consequences and the adaptive and mitigation responses needed to safeguard livestock systems and global food security.

Keywords: Livestock Emissions, Carbon Footprint, Animal Health, Mitigation Strategies.

1. Introduction:

The global food system significantly contributes to greenhouse gas (GHG) emissions, and the livestock sector is a major part of this system. Livestock supply chains, such as feed production, enteric fermentation, manure management, transport and land-use changes, are estimated to make up a large portion of human-caused emissions. This is measured in billions of tonnes of CO_2-equivalent each year. These emissions create a two-way relationship: animal agriculture contributes to climate change, and climate change then affects the biological, economic and social conditions for raising animals. This leads to various consequences for animal health and welfare, productivity, farmer livelihoods, food security and the overall goal of sustainable development (FAO, 2024).

2. Direct Biological Consequences for Animals

2.1 Heat Stress, Physiology and Productivity

Rising temperatures and more frequent heat waves undermine animal physiological homeostasis. Heat stress reduces feed intake, alters metabolic rates and impairs reproductive function. In dairy cattle, even moderate heat stress depresses milk yield, reduces conception rates and increases embryonic loss. Poultry and swine also show marked reductions in growth rates and egg production as ambient temperatures rise. These physiological disruptions are not one-off events but repeated seasonal heat stress can produce chronic productivity losses across herds and flocks (Godde *et al.,* 2021).

2.2 Disease, Parasites and Changing Pathogen Ranges

Warmer climates and changing precipitation patterns expand the geographic range and seasonality of many vectors (ticks, mosquitoes, biting flies) and pathogens. Diseases once restricted to tropical or subtropical zones are moving into temperate regions, and endemic disease burdens can intensify in marginal environments. Weaker immune function in heat-stressed animals compounds susceptibility. Increased disease prevalence raises morbidity and mortality, drives up veterinary costs and threatens trade in animal products (Abbasi, 2025).

2.3 Nutrition and Feed Quality

Climate change also affects forage quantity and quality. Droughts, altered rainfall timing and elevated CO_2 levels can lower the protein and micronutrient content of grasses and crops used in feed, reducing digestibility and animal performance. Feed scarcity forces change in feeding strategies (more reliance on purchased concentrates, crop residues of lower quality, or overgrazing), which in turn affect herd productivity and resilience. (Rojas-Downing *et al.,* 2017).

3. Systemic Economic and Livelihood Impacts

3.1 Reduced Productivity and Income

The combined effect of heat stress, increased disease and poorer feed leads to lower yields of milk, meat, eggs and wool. These reductions translate quickly into economic insecurity for smallholder households that depend on one or a few animals as assets or income sources. Veterinary interventions and increased mortality further erode livelihoods. At scale, production declines can affect supply, prices and the stability of rural economies (Godde *et al.,* 2021).

3.2 Market Disruptions and Trade

Climate impacts are not uniform. Some regions may see sharper productivity loss than others. Uneven regional effects can disrupt commodity flows and increase price volatility. Export-dependent producers may face new regulatory and market barriers (carbon-related tariffs or buyer requirements) as importing countries and retailers tighten sustainability criteria. This

creates both risks and incentives for producers to reduce their carbon footprints (Dida *et al.,* 2025).

3.3 Costs of Adaptation and Mitigation

Adapting animal systems to a warming world requires investment: shade structures, cooling systems, improved housing, altered feeding regimens and veterinary services. Similarly, mitigation measures to reduce the sector's carbon footprint such as feed additives that lower enteric methane, improved manure handling or land-use changes, carry up-front costs and may require new supply chains, knowledge transfer and regulation. Financing these changes is a major barrier for many small-scale producers (Souza *et al.,* 2024).

4. Food Security and Public Health Consequences

Animal products are nutrient-dense and central to many diets worldwide. Decline in production or disruptions in distribution can threaten local and national food security, particularly in regions where livestock are primary sources of protein and micronutrients. Additionally, climate-driven changes in disease patterns can increase zoonotic risks and necessitate more intensive surveillance. Any mitigation technology or management change must be assessed for food safety implications and consumer acceptance (Owino *et al.,* 2022).

5. Environmental Consequences

The animal sector's carbon footprint includes not only CO_2 but also methane (CH_4) and nitrous oxide (N_2O), both potent climate forcers. Methane from enteric fermentation and manure is especially important because of its strong near-term warming effect. Land clearing for pasture and feed crops releases stored carbon and reduces ecosystem carbon sinks. These emissions accelerate climate change, which in turn deepens the stresses faced by livestock, a reinforcing feedback loop. Tackling the sector's emissions is therefore both a mitigation priority and a way to slow future animal-sector harms (Nugrahaeningtyas *et al.,* 2024).

6. Mitigation Strategies and Sector Responses

6.1 Productivity and Efficiency Gains

Improving feed conversion efficiency, selective breeding for productivity, resilience and better herd management reduces emissions per unit of product. Efficiency gains can be win-wins: higher output and lower emissions intensity. However, absolute emissions depend on production scale. Efficiency alone may not reduce total emissions without complementary measures (Giamouri *et al.,* 2023).

6.2 Enteric Methane Reduction Technologies

A promising suite of interventions targets enteric methane: feed additives (3-nitrooxypropanol or 3-NOP), certain seaweed extracts (*Asparagopsis* spp.), oil supplements and precision feeding. 3-

NOP has been shown in multiple trials to reduce methane by 30–40% while sometimes improving feed conversion; seaweed extracts have delivered even higher reductions in experimental conditions, though scaling, supply chain and sustainability of harvesting/cultivation remain concerns. Widespread adoption depends on regulatory approvals, cost, supply and public acceptance (Yu *et al.,* 2021).

6.3 Manure Management and Circular Practices

Better manure handling (covered storage, anaerobic digestion for biogas) can cut methane and nitrous oxide emissions, create renewable energy and produce biofertilizer. Integrating livestock with crop systems *ie*., using manure to fertilize feed crops, can close nutrient loops and reduce reliance on synthetic fertilizers, lowering the sector's overall carbon intensity (FAO, 2024).

6.4 Land Management and Carbon Sequestration

Avoiding deforestation for pasture, investing in silvopastoral systems (trees integrated with grazing) and restoring degraded pastures can increase on-farm carbon sequestration and improve resilience (shade, shelter, improved forage). Some regions have demonstrated notable emission reductions through reduced land clearing and increased vegetation growth. These approaches can provide co-benefits for biodiversity and microclimate regulation. (Aryal *et al.,* 2022).

6.5 Policy, Market and Behaviour Changes

Policy tools (carbon pricing, subsidies for low-emission technologies, regulations on land-use change) and market signals (sustainability procurement criteria, carbon-labelled products) shape producer decisions. Consumer behaviour such as dietary choices and demand for lower-footprint products, also influences how quickly the sector shifts. Ensuring equitable transitions is critical: smallholders must be supported so they are not disproportionately penalized (FAO, 2024).

6.6 Risks, Uncertainties and Co-Benefits

While promising, mitigation options face uncertainties: long-term efficacy (e.g., durability of methane reductions), unintended consequences (animal health, product quality), socio-economic feasibility, and scaling constraints. There are also potential co-benefits: better animal welfare, reduced local pollution and energy generation from biogas. Decision-making should weigh trade-offs and prioritize measures that deliver multiple benefits (Malyugina *et al.,* 2025).

7. Policy and Sectoral Recommendations

- **Prioritize resilient production systems:** Invest in heat-mitigation measures (shade, water, housing) and climate-smart breeding and feed strategies to protect animal welfare and productivity

- **Scale proven methane mitigation technologies responsibly:** Accelerate regulatory assessment and supply chain development for additives like 3-NOP and sustainable seaweed cultivation, paired with transparent communication to address public concerns
- **Support smallholders financially and technically:** Provide access to credit, extension services and cost-sharing for adaptation and low-carbon investments so that vulnerable producers can participate in transitions.
- **Integrate mitigation with adaptation:** Favor interventions that reduce emissions intensity and build resilience (silvopasture, improved manure systems).
- **Strengthen surveillance and research:** Expand monitoring of animal health, productivity and emissions; fund research into long-term effects of micro-interventions; and quantify socio-economic impacts.
- **Align policies with food security goals:** Avoid measures that undermine local nutrition; use targeted policies to balance climate mitigation with the need for affordable, nutritious animal-sourced foods.

Conclusion and Future Directions:

The carbon footprint of the animal sector creates both a responsibility and an opportunity. The sector contributes meaningfully to global emissions, yet it also underpins livelihoods, culture and nutrition for billions. The consequences of continuing on a high-emissions trajectory are clear: worsening animal health, lower productivity, economic strain for farmers, and heightened food security risks. But evidence also points to tangible mitigation pathways from feed additives and manure management to land-use change and policy reform that can reduce emissions while improving resilience and productivity. The challenge is operational: mobilizing finance, building supply chains for new technologies, supporting smallholders, and crafting policies that are scientifically sound and socially equitable. With coordinated action across producers, researchers, industry and governments, the animal sector can lessen its carbon footprint while safeguarding the food systems and livelihoods that depend on it.

References:

1. Abbasi, E. (2025): Climate Change and Vector-Borne Disease Transmission: The Role of Insect Behavioral and Physiological Adaptations. *Integr Org Biol.,* 7(1): obaf011.
2. Aryal, D.R., Morales-Ruiz, D.E., López-Cruz, S., Tondopó-Marroquín, C.N., Lara-Nucamendi, A., Jiménez-Trujillo, J.A., Pérez-Sánchez, E., Betanzos-Simon, J.E., Casasola-Coto, F., Martínez-Salinas, A., Sepúlveda-López, C.J., Ramírez-Díaz, R., La O Arias, M.A., Guevara-Hernández, F., Pinto-Ruiz, R. & Ibrahim, M. (2022). Silvopastoral systems and

remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. *Sci Rep.*, 12(1): 16769.

3. Dida, M.F., Garcia, S.C. & Gonzalez, L.A. (2025). Greenhouse gas emissions of confinement and pasture-based dairy farms: Implications for mitigation. *J Dairy Sci.*, 108(10): 11026-11040.
4. FAO. (2024). Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000–2022. Retrieved from https://www.fao.org/statistics/highlights-archive/highlights-detail/greenhouse-gas-emissions-from-agrifood-systems.-global--regional-and-country-trends--2000-2022/en?utm_source=chatgpt.com
5. Giamouri, E., Zisis, F., Mitsiopoulou, C., Christodoulou, C., Pappas, A. C., Simitzis, P. E., Kamilaris, C., Galliou, F., Manios, T., Mavrommatis, A., & Tsiplakou, E. (2023). Sustainable Strategies for Greenhouse Gas Emission Reduction in Small Ruminants Farming. *Sustainability*, 15(5), 4118.
6. Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K. & Herrero, M. (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. *Glob Food Sec*., 28: 100488.
7. Malyugina, S., Holik, S. & Horky, P. (2025). Mitigation strategies for methane emissions in ruminant livestock: a comprehensive review of current approaches and future perspectives. *Front. Anim. Sci.,* 6: 1610376.
8. Nugrahaeningtyas, E., Lee, J.S. & Park, K.H. (2024). Greenhouse gas emissions from livestock: sources, estimation, and mitigation. *J Anim Sci Technol*., 66(6): 1083-1098.
9. Owino, V., Kumwenda, C., Ekesa, B., Parker, M.E., Ewoldt, L., Roos, N., Lee, W.T. & Tome, D. (2022). The impact of climate change on food systems, diet quality, nutrition, and health outcomes: A narrative review. *Front. Clim*. 4:941842.
10. Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., & Woznicki, S.A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag*., 16:145–163.
11. Souza, W.L.D, Niehues, M.B., Cardoso, A.D.S., Carvalho, V.V.D., Perdigão, A., Acedo, T.S., Costa, D.F.A., Tamassia, L.F.M., Kindermann, M., & Reis, R.A. (2024). Effect of 3-Nitrooxypropanol Combined with Different Feed Additives on Growth Performance, Carcass Traits, Enteric Methane Emissions, and Physiological Responses in Feedlot Beef Cattle Fed a High-Concentrate Finishing Diet. *Animals*, *14*(23): 3488.
12. Yu, G., Beauchemin, K.A. & Dong, R. (2021). A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. *Animals*., 11(12): 3540.

SUSTAINABLE ENERGY EFFICIENT AND ECONOMICAL INDUSTRIAL FACILITY DESIGN

Vivekanand Shere*, Hiraman Jadhav, Yogesh Shirke and Prashant Titare
Department of Electronics and Telecommunication Engineering,
D. Y. Patil College of Engineering, Akurdi, Pune, Maharashtra, India
*Corresponding author E-mail: vbshere@dypcoeakurdi.ac.in

Abstract:
Industrial facilities are rapidly changing over the years; various technological advances have led to break-through its performance. The transformation is fetched from inventions, development of sophisticated processes/technologies, digitalization, the list is incessantly growing. These technical progressions and stratagems to realize it on the life-cycle basis forces the industries to explore sustainability concepts within the scope. Also, the mission to chop back GHG emissions to protect environment is needed than ever before. Consequently, the revolution and evolution of products, processes, technologies, resources, and sustainability requirement to mitigate climatic anomaly beams on the industrial sector and ordained it to cater an approach toward optimizing all efforts. The challenge is to develop a method by accommodating all the technological advances and sustainability requirements to transform facilities into a much better performing asset. The answer is to construct and preserve industrial facilities to be energy efficient & more economical which enable them to be competitive and environmentally friendly. The chapter illustrates, through case study, the 'plant lifetime retrofit- ability concept in industrial facilities. Its objective is to develop the most energy efficient & economical facility design via arranging each future modification to remain energy efficient throughout its lifecycle without deterrents and utilizing minimum capital hence more economical. Finally, a way is proposed to develop inherently sustainable energy efficient & economical design in order to cater the benefits throughout the industrial facility life-cycle.

Keywords: Energy Efficiency, Sustainability, Energy Integration, Pinch Technology, Process Integration, Retrofit, GHG Emissions Reduction, Facility Design, And Oil and Gas.

1. Introduction

Industrial sector relies on fossil fuels as the primary source of energy that is in control of approximately one-third of world-wide energy usage. A major percentage of energy consumed is disbursed to provide utilities for oil & gas facilities in order that energy may well be engendered for other sectors. The adverse impact of fossil- fuel combustion has instigated efforts to attenuate

carbon emissions, whilst environmental regulations have a considerable effect on the energy's cost. Furthermore, it's a competitive world with ever-increasing energy prices, industrial communities are convened to brainstorm over conservation of energy resources and profitability. Energy efficiency should be a foundational strategy to support plans to fulfill the cli- mate policy goals moreover as for being lucrative. Energy efficiency with its integral role in energy intensive industrial processes is critically essential to realize desired energy-saving potential and reduction in Carbon Dioxide gas (CO_2) emissions.

The economics of industrial production, environmental conservation realities and global energy supply limitations are persistent concerns for the whole industrial sector. Regardless of where on turns, there's an unswerving appeal to preserve energy, reduce carbon emissions, and safeguard environment for future generations. These enablers made energy efficiency as an entrenched thanks to conduct the business. In fact, energy efficiency for any industrial facility (i.e. several processes/plants tied with a central utilities-plant) is extremely dynamic and wish to be improved through- out its lifetime, nonetheless of how energy-efficient facility design was achieved during design-phase. On the opposite hand, in its entire lifetime, a plant undergoes various retrofit subjected to high-profile operational changes/improvements/profits. The changes that include process disturbances, uncertain feedstock conditions, and products demand are short-term, requiring no major retrofit. However, long-term transformations comprise of must process more raw feed, feedstock changes, improve performance etc. warrants the debottlenecking of the whole facility and comprises key retrofits. In summary, may be stated that, the retrofitting of a plant may well be needed numerous times, in its lifespan, to upgrade energy efficiency and satisfy the required increase in production rates.

The main challenge is to develop the proposed facility design into a Sustainable Energy-Efficient Design, which implies a design that's capable of improving its energy efficiency supported by the energy-capital trade-off dynamics. Conceptually the problem will be formulated as a bi-level programming problem with two objectives, the minimum disruption within the energy utility supply (zero deficiency) and minimum energy utility consumption. In such cases the energy utility is minimized subject to least energy deficiency in supply. The outer problem of optimization of minimum energy consumption should be solved at the best-case scenario of the inner problem which is that the least possible deficiency in energy utility supply to the process plant.

On the macro level, there are three energy system components i.e. generation, distribution and utilization. Throughout the process facility design, the main target is to boost all three components of energy i.e. energy demand (process/user) minimization, efficiently fulfill energy demand

(efficiently site-wide utility/supplier) and efficiently transport energy from supplier(s) to user(s). Objectives are to minimize: waste in energy, fresh resources and capital (de-bottlenecking) in these three components. This may be done via the continual upgrade of the efficiency of energy system components in generation, distribution and utilization. However, the utilization component has a unique feature, where its boundaries do not seem to be completely dictated by the process/users. Therefore, the space of improvement within this component is way wider than the others. The interaction among all three components specified waste from one component to be utilized by others and also modifications of one component supported the other components waste availability will suffice in developing energy efficient process design. Moreover, as highlighted earlier that over the last forty plus years several design standards/criteria aside from safety; health and environment besides capital and operating costs are considered, like switch-ability; flexibility; reliability; maintainability; availability; controllability; operability; acceptability and then on. Although, almost every industrial facility has to be retrofit- ted several times throughout its lifetime to satisfy its objectives which was coined as "retrofit with retrofit in mind approach". "Retrofit-ability" as a design requirement has not been addressed or may be coined within the chemical engineering design community until recently. It's worthwhile to say that the chapter emphasize to develop sustainable energy efficient design by reducing the process facility demand i.e. the utilization energy component of the process.

Thus, each facility design may be a result of process synthesis which represents the configuration of the varied pieces of equipment and their interconnection represented on a flowsheet. It's almost impossible to induce a sustainable energy efficient facility design if the definition includes process synthesis as a part of the definition, humans are always in pursuit of excellence through knowledge and it has no practical limits. New discoveries will be made and new processes are going to be synthesized to attain the identical outcomes with meager energy and capital in an exceedingly more environment friendly manner. Because the facility could not be designed to cater inventions, consequently the inclusions of it within the sustainable energy efficient facility design definition is not defensible. Hence, the definition of sustainable energy efficient facility design does not embrace process synthesis but it lies within the response of the question i.e. the way to intensify facility design for a specified process which is capable of improving its energy efficiency grounded on the energy-capital trade-off throughout its life cycle. The foremost hurdle to achieve such a design is its acceptance to "retrofit", because the design has to be adapted several times during its life-cycle to be energy efficient. It will not be erroneous to conclude that the aspect of retrofit-ability could be a precondition for a sustainable energy efficient design [1, 2].

1.1: Retrofits

It is palpable that "Retrofits" are very significant to accomplish desired goal of developing sustainable energy efficient facility design. Retrofit/Revamp is defined as modification of a plant or facility to boost efficiency, reduce emissions and/or change capacity, and make it adequate for a replacement design or operating condition. Chemical engineering design community over the last forty plus years has considered several design criteria aside from safety; health and environment (SHE) besides capital and operating costs, like switch-ability; flexibility; reliability; maintainability; availability; controllability; operability; acceptability and then on. It's true that any industrial facility has to be retrofitted several times during its lifetime to meet its purposes. However, "Retrofit-ability" as a design obligation has not been addressed or maybe coined within the chemical engineering design community till some recent works, it necessitates attention of community as emissions reduction and competitiveness are sought than ever before [3–5].

There might be various objectives for a retrofit, as an example, GHG emissions reduction, utilities savings, throughput increment, modifying appropriate network topology, upgrading heat transfer units, installing additional heat transfer area, re- piping streams and re-assigning heat recovery matches etc. Pinch technology imparts a systematic technique based on thermodynamics, design and economics heuristics for saving energy in processes and on entire sites. This procedure helps optimize thermal heat recovery, and immediately became popular as a theoretically elegant yet feasible approach to scheme Heat Exchanger Networks (HENs). Heat exchanger net- works (HENs) are widely applied in industrial projects over the past decades because they offer significant energy and economic savings. Applications of HEN integration is divided into two categories i.e. grassroots and retrofit design. In oil refining, retrofit design are way more common than grassroots applications. The retrofit objective is to spot an economical HEN, subject to many design and operating constraints.

1.2: Sustainable Energy Efficient and Economical Facility Design:

Retrofits are almost inevitable for a facility to be energy efficient & economical throughout its life-time, but it emanates with shut-down, structural (process/HEN topology) and plot-plan limitations. Altogether, these constraints make retrofit infeasible and consequently facility energy inefficient at some point in their life-time. Thus, to achieve sustainable energy efficient & economical design a much-sought criterion is that the design that may be successfully retrofitted during the course of its life time. Retrofit-ability could be a pre-requisite criterion for the sustainable energy efficient & economical facility design and wishes to be entrenched within the design.

A healthy-aging design supported by retrofit-ability criterion i.e. no shut-down obligation, no proposed topology alteration or no-plot plan limitations for the execution of all energy efficiency projects will be energy efficient through-out its life time. Subsequently, "Sustainable Energy Efficient Facility Design" will be demarcated as a design for a given facility which shall be capable to acclimatize any essential modification for energy efficiency (i.e. trade-off between energy cost reduction and capital investment) at any point in its life-time with none restraint owed to its existing design. The sustainable energy efficient design is capable of adjusting to the dynamic trade-off between energy cost reduction and capital investment supported the principle of energy targeting without feasibility limitations because of present design throughout its life time. It shall be developed as a design supported energy- capital trade-off changing aspects from the beginning of its life-cycle till the termination. All essential modifications shall be planned and provision is formed within the initial design to include deviations with the identical or less capital as for a brand-new design with the identical energy values.

Minimum Energy Requirement (MER) of a facility may be a subject that ride the methodology pragmatic to focus on the demand, targets among the plants may be generated supported direct/indirect integration or the other technique. Although, Pinch approach which is widely utilized in industry to get energy targets utilizes indirect targeting methodology i.e. each process has energy targets (based on direct integration) and also the integration among the processes is indirect i.e. via buffer systems like through steam headers.

2. Related Work

Process design has evolved from inventions of recent design based upon experiments to today's novel process flow-sheet synthesis based-upon optimization. It responded to through a generation of process design based-upon the concept of stand-alone unit operations and therefor the integration between unit operations. The development of varied systematic design techniques supported on process integration has made it a promising tool in resource conservation activities. Improvement opportunities shall be identified either as process modification or design improvement as compared to the base case energy consumption regardless of the approach applied. As some approaches try to improve the energy performance of the facility design on extempore basis rather than developing it with an organized approach.

2.1: Primitive Approach

In primitive facility design approach (Figure 1), only core process was designed and utility was provided for all energy consumption i.e. heating, cooling or shaft work with none concept of energy efficiency or perhaps utility targeting. Consequently, the two elements were designed separately with none emphasis on energy efficiency and also the process design is directly dictating the utility

system design and there aren't any interactions among systems to boost the facility design. This approach was in practice when the efficient utilization of the resources wasn't priority in any aspect facility design. Nowadays, the approach is sort of extinct for the mass production in process industries, can be found in practice for very small-scale production or for batch processes or processes where the production mechanism is not fully known or could not be controlled with needed accuracy.

The approach is incredibly simple to implement and used generally for complex batch processes, because it is incredibly difficult to integrate them.

Figure 1: Primitive approach of facility design

As process and utilities systems are designed separately, only individual systems might be improved and advantages of integration cannot be realized utilizing this approach.

2.2: Conventional Approach

At this time, the efficient utilization of resources and particularly of energy has become a matter of priority in many aspects of industrial and social planning. The accepted reason is that the rapid increase within the cost of key resources which has made a reappraisal of the many adopted practices necessary. Additionally, there seems to be a case for efficient resource utilization whether it would not be economically justified yet: dwindling raw materials will tend to steer further price increases - and scarcities - within the future and conservation in time will help to arrange for such a course of events. Industry was beholding to enhance for energy conservation and to reduce negative environmental impacts but there was no systematic approach to attain it within the past. The improvements were only supported by observations and lessons learned from the previous experiences, sometimes energy optimization problem was very narrowly defined to realize these shown

improvements locally which could have adverse effect at a higher level. Accordingly, the facility design approach as shown in Figure 2, is improved but only on unpremeditated basis, still no interactions were studied to boost the facility design systematically.

Figure 2: Conventional approach of facility design.

3. Recommended Systems and Proposed Methodology

3.1. Adu-Vdu Plant Sustainable Energy Efficient Design

Oil refineries are vital to the global economy and at the identical time major consumers of energy. Petroleum refineries are under increased pressure to reduce emissions of greenhouse gases, mainly CO_2 to accommodate with the upcoming stricter environmental regulations. Energy efficiency optimization may be a means solution to GHG emissions reduction because of its impact on energy consumption at the source. Heat exchangers play a significant role in crude oil refineries in energy saving, in general. Distillation is that the main consumer of energy in a crude oil refinery, and heat exchangers connected together in what's called a preheat train are essential to dramatically reduces the thermal duty of the atmospheric crude unit furnace. Crude distillation could be a primary processing operation in refineries throughout the planet and requires heat, steam and cooling to work. Although the crude distillation unit (CDU), that consists of both atmospheric distillation unit (ADU) and also the vacuum distillation unit (VDU), is not the foremost energy-intensive plant within the petroleum refinery, in terms of energy per barrel, every barrel of oil that is processed within the petroleum refinery passes through this unit/ plant, making it the most important energy consumer, of the entire energy consumed, in fossil oil refineries.

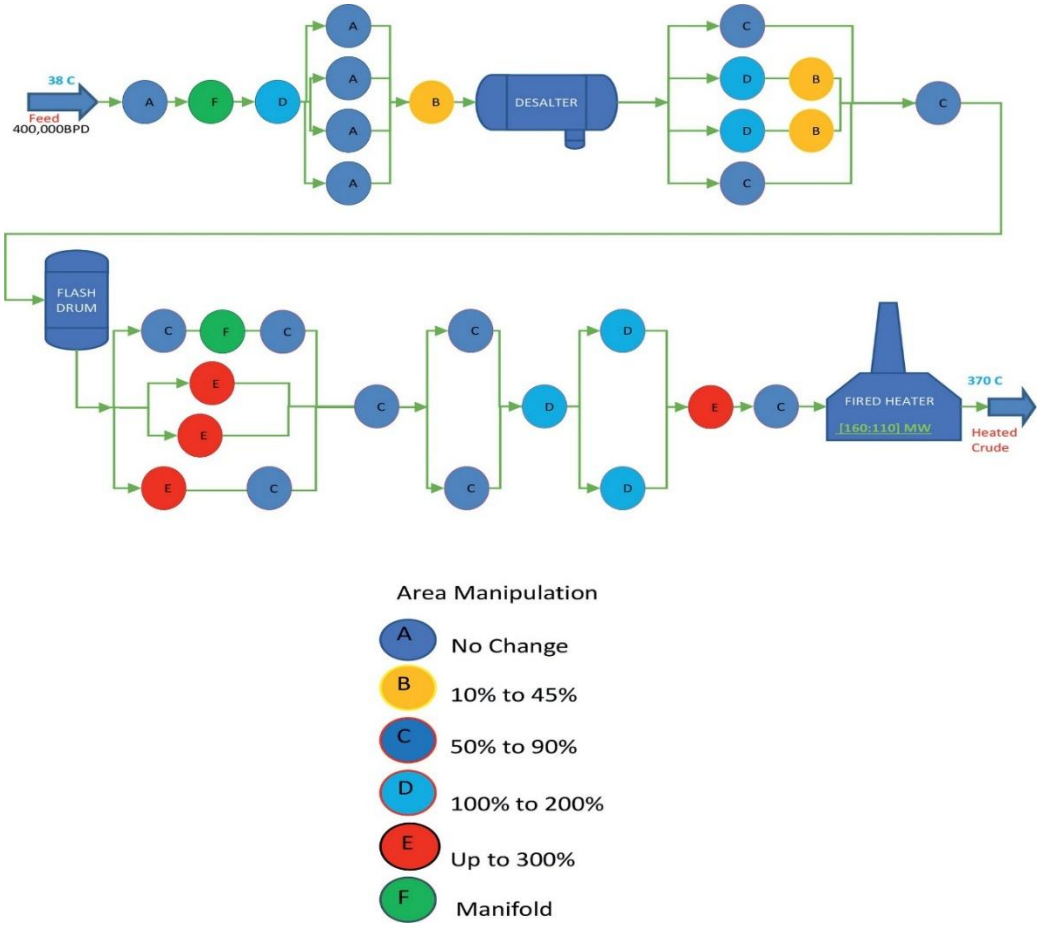


Figure 3: ADU-VDU sustainable energy efficient & economical design.

Crude distillation process separates fossil oil into fractions in keeping with boiling point so that down-streams processing plants are often charged with feedstock that meets their particular specifications.

Crude oil separation process is accomplished by first fractionating crude petroleum at essentially atmospheric pressure and then feeding the high-boiling fraction, called topped crude or reduced crude, from the atmospheric distillation tower bot- toms to a second fractionation tower that's operated under vacuum conditions. The invention renders novel pre-heat sustainable design from energy consumption efficiency and fossil fuel-based GHG emissions' points of view along the fossil oil refinery lifetime solely; through the pre-heat train heat exchangers' surface areas manipulation as shown in fig.3. This invention enables the crude oil refineries to know ahead of time their plot plan needs for future crude distillation units furnace debottlenecking and/or energy saving projects. The invention shown embodiment exhibits the small print of the pre-heat train's design for the Minimum Approach Temperatures Range of 30^0C to 15^0C and further the thermal duties of heat exchangers (Q) in MW and temperatures in ^{0}C.

Conclusions and Recommendations:

To develop sustainable energy efficient & economical design facility design evolutionary-approach shall be adapted rather than the more time-consuming revolutionary-approach. The concept is to develop sustainable energy efficient process design of every individual process, which itself is challenging but might be realized. Subsequently, once all the processes are sustainable the facility is going to be sustainable in energy efficiency develop options for inter/intra/hybrid integration together with energy recovery technologies to form the facility "best in class" from energy perspective.

Definitely obtaining a sustainable energy efficient & economical design facility design is extremely challenging but the advantages from its enormous, even a design from only heat integration perspective are great. If a design, even at a process level from heat integration perspective is produced such it's fixed topology i.e. no new stream matches and energy efficiency improvements by area manipulation only will ends up in high energy as well as monetary savings. This is demonstrated through ADU- VDU sustainable design for a 400,000 BPD refinery, the advantages include energy savings of about $100 million NPV (depending on energy vales) together with about 90 kilo tons of CO_2 emissions reduction annually. The modification to boost energy efficiency does not require extended shut-down for energy projects but may well be drained normal shut-down window.

Figure 4 summarizes the benefits of Sustainable Energy Efficient Economical Design benefits, as the solutions are "off the shelves" design i.e. pre-engineered, it does not have shut-down, structural and/or plot plan limitations.

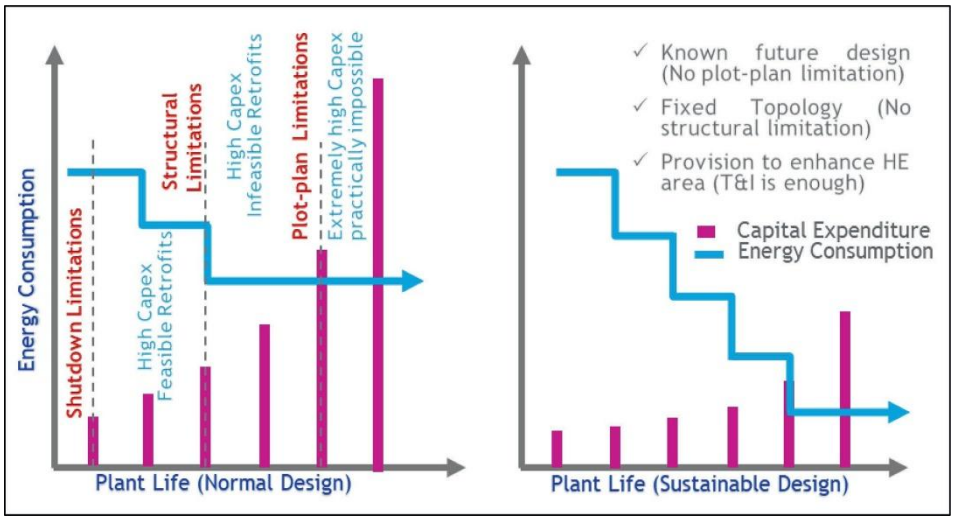


Figure 4: Comparison between Normal versus sustainable energy efficient and economical design

Retrofits in normal design are generally limited initially by shut-down opportunities as initially energy savings projects are feasible but later obstructed by structural limitations which implies the topology can either restricted or resulted in retrofits with very high capital and ends up with the area constrains may leads to impracticable retrofits. The constrains of shut-down, structural and plot-plan limits the facility to be energy efficient solely up to a particular level which will not able to be energy efficient supporting the economic trade-off for its life-time. On the other hand, the capital needed to do the modifications is much less in sustainable design as the provision for the modifications were made during initial design. Consequently, the initial as well as final facility design are very close to be energy efficient based on the economic trade-off. Hence, it is highly recommended for all chemical engineering community to come together for develop- ing methods, techniques and frame-work to achieve "Sustainable Energy Efficient Plant Design" and extend it to achieve the ultimate goal of "Sustainable Energy Efficient Facility Design".

Nomenclature

ADU	Atmospheric Distillation Unit
BPD	Barrels Per Day
C	Degree Celsius
CDU	Crude Distillation Unit
CO_2	Carbon Dioxide
GHG	Green House Gas

HE	Heat Exchanger
HEN	Heat Exchanger Network
MER	Minimum Energy Requirement
MW	Mega Watt
NPV	Net Present Value
Q	Heat Duty of Heat Exchanger
RAM	Reliability, Availability and maintainability
SHE	Safety Health and Environment
VDU	Vacuum Distillation Unit

References:

1. Farooq, Z., & Almutairi, S. (2022). Low-cost retrofits to improve efficiency at Aramco refinery. *Oil & Gas Journal, 120*(1), 41–45.
2. Farooq, Z., & Almutairi, S. (2022). Pinch analysis spots design retrofits to support future unit upgrade. *Oil & Gas Journal, 120*(2), 31–36.
3. Noureldin, M. B., & Farooq, Z. (2020). *Refinery pre-heat train systems and methods* (U.S. Patent Nos. 10,494,576; 10,822,551 B2).
4. Micieta, B., Markovic, J., & Binasova, V. (2016). Advances in sustainable energy efficient manufacturing system. *MM Science Journal, 2016*(06), 918–926.
5. IPIECA. (2013). *Pinch analysis*. Available from: https://www.ipieca.org/resources/energy-efficiency-solutions/efficient-use-of-heat/pinch-analysis/
6. Noureldin, M. B. (2012). *Systems and program product for heat exchanger network energy efficiency assessment and lifetime retrofit* (U.S. Patent No. 8,150,559).
7. Noureldin, M. B. (2012). *Methods for heat exchanger network energy efficiency assessment and lifetime retrofit* (U.S. Patent No. 8,150,560).
8. Asanta, N. D. K., & Zhu, X. X. (1996). An automated approach for heat exchanger network retrofit featuring minimal topology modification. *Computers & Chemical Engineering, 20*, 7–12.
9. Biegler, L. T., Grossmann, I. E., & Westerberg, A. W. (1997). *Systematic methods of chemical process design*. Prentice Hall.
10. Linnhoff, B. (1993). Pinch analysis—State of the art overview. *Transactions of the Institution of Chemical Engineers, Research and Design, 71*(A5), 503–522.
11. Ciric, A. R., & Floudas, C. A. (1991). Heat exchanger network synthesis without decomposition. *Computers & Chemical Engineering, 15*, 385–396.

SMART AC CHARGING MANAGEMENT SYSTEM FOR ELECTRIC VEHICLES

R. Elavarasi*, S. Murugesan, S. Selva Kumar, S. Aravindan and S. Vishwas

AMET Deemed to be University, Chennai, India.

*Corresponding author E-mail: elavarasir2014@gmail.com

Abstract:

The abstract summarizes the entire charging controller project by highlighting the need for reliable and safe transfer of electrical energy from the grid to electric vehicles. It explains that the system incorporates a low-power AC-DC auxiliary converter, pilot signal communication, and leakage protection to comply with international standards. In addition, it briefly mentions the inclusion of a fluxgate-based sensor for both AC and DC ground-fault monitoring, supercapacitor-based emergency power supply, and efficient relay control. The abstract concludes by stating that these integrated features enhance the overall safety, reliability, and efficiency of EV charging operations.

Introduction:

Electric vehicles (EVs) have emerged as a major solution to global concerns such as rising fuel prices, urban air pollution, and the need to transition toward sustainable and eco-friendly transportation. As EV adoption rapidly increases across personal, commercial, and industrial sectors, the supporting charging infrastructure has become just as critical as the vehicles themselves. To ensure that EVs remain practical and functional for everyday use, users must have access to chargers that are fast, reliable, safe, and capable of operating under a wide range of electrical and environmental conditions. Among the available charging options, AC Level-2 chargers have gained significant popularity because they can provide faster charging times compared to domestic Level-1 chargers, yet they do not require the complex and high-cost electrical installation associated with DC fast charging systems. AC chargers also offer flexibility, enabling installation in homes, workplaces, commercial parking facilities, and public charging networks. Despite these advantages, developing a robust AC charging system is not straightforward, as it must meet several engineering and regulatory requirements to ensure safe and optimal operation for both the vehicle and the user. One of the most critical challenges is maintaining proper communication between the charger and the vehicle. International standards such as IEC 61851 and SAE J1772 define communication protocols, particularly the use of a pilot signal that informs the vehicle of the available current and charging status. This signal must be interpreted accurately to ensure stable charging and to prevent damage or unsafe conditions.

Another major requirement is the protection of users and equipment against electrical hazards. During charging, leakage currents can arise due to insulation faults, component failure, or environmental exposure. While AC leakage may trip standard protective devices, DC leakage is more dangerous because it can saturate residual-current systems and go undetected. Therefore, modern EV chargers must incorporate advanced sensing mechanisms capable of detecting both AC and DC leakage and responding rapidly to eliminate the hazard. Additionally, the system must ensure the safe operation of relays and contactors, which connect and disconnect power during charging. If relay contacts weld due to electrical arcing or mechanical wear, they could remain stuck in a closed position, continuing to deliver power even after the system attempts to shut down. This means that chargers require not just strong relay drivers but also weld-detection mechanisms that can verify whether contacts have opened or closed correctly.

Literature Review:

Electric Vehicle Supply Equipment (EVSE) plays a key role in charging electric vehicles safely and efficiently. Many studies highlight the importance of international standards such as SAE J1772 and IEC 61851, which define the control pilot signal used for communication between the charger and the vehicle. Research also emphasizes the need for safety through Residual Current Detection (RCD) to protect against both AC and DC leakage currents. Recent designs focus on reducing standby power consumption using efficient AC/DC converters and supercapacitor backup systems that maintain power during grid failures. Literature further shows the importance of efficient relay drivers and weld detection methods to ensure safe disconnection of power. Overall, existing work demonstrates reliable and cost-optimized approaches for AC Level 2 chargers, but opportunities remain to improve efficiency, diagnostics, and real-world testing.

Objectives of the Study:

The main objective of this work is to design and develop a smart and energy-efficient AC Level-2 electric vehicle charging controller capable of delivering safe, reliable, and standards-compliant charging in real-world conditions. The system aims to provide stable power conversion through a low-standby isolated AC-DC supply that minimizes energy loss when the charger is not actively in use. Another major goal is to ensure user and equipment protection by integrating comprehensive safety features, including real-time monitoring of both AC and DC leakage currents, rapid fault isolation, and reliable relay and contactor operation. The project also seeks to guarantee uninterrupted system shutdown even during sudden mains failure, which is achieved by incorporating a supercapacitor-based emergency backup system capable of powering critical circuits long enough to release relays and return the system to a safe state.

Technological Need and Industry Evolution

The global transportation landscape is undergoing a major transformation driven by the rapid growth of electric vehicles, government policies encouraging decarbonization, and increasing environmental awareness among consumers. As countries push toward reducing greenhouse gas emissions and decreasing dependence on fossil fuels, electric vehicles are becoming a central component of sustainable mobility strategies worldwide. However, the success of EV adoption does not depend solely on the vehicles themselves but also heavily on the development of a reliable, accessible, and efficient charging ecosystem. Without dependable charging infrastructure, even the most advanced EVs would face limited practicality, range anxiety, and reduced consumer confidence. Therefore, the development of intelligent, medium-power AC chargers is essential because they provide a balance between performance and cost, making them suitable for homes, offices, commercial installations, and public networks. AC Level-2 chargers, in particular, are more appealing because they offer significantly faster charging than standard household outlets without requiring the expensive, high-power conversion equipment associated with DC fast chargers. Their flexibility and relative affordability have made them a preferred choice in expanding infrastructure grids internationally. As the industry evolves, the complexity of AC charging systems has also increased. Modern chargers are expected to do much more than simply deliver electrical power; they must communicate seamlessly with the electric vehicle, follow global interoperability requirements, and protect users from electrical and mechanical hazards. Elements such as pilot signaling, automatic current limitation, and detection of charging states must comply with standards like IEC 61851 and SAE J1772 to guarantee that vehicles from different manufacturers can safely use the same charging stations. These standards specify how the vehicle and charger exchange information using PWM control signals, determine the maximum allowable current based on the duty cycle, and communicate fault conditions or charging readiness. In addition to this, the growing number of EVs connected to the grid simultaneously requires that chargers consume minimal standby power when not actively charging. Even a small reduction in standby consumption can lead to major energy savings when multiplied across millions of chargers installed worldwide. Therefore, energy-efficient design is not only a technical requirement but also an economic and environmental necessity.

Another driving factor behind this work is the increased focus on electrical safety in the charging environment. High-power charging systems operate in outdoor, industrial, and public areas were environmental exposure, component aging, or wiring faults can cause hazardous leakage currents. Traditional protection devices may detect AC leakage but often fail to detect DC leakage, which can saturate protection coils and leave users unprotected. This limitation has led

modern charger designs to incorporate advanced sensors that can detect both AC and DC leakage in real time and trigger rapid shutdown of the system. Additionally, safe switching of relays and contactors has become a critical concern in the industry. When relays weld due to mechanical or electrical stress, they may remain permanently closed, continuing to supply power even after the charger attempts to disconnect, posing a severe safety hazard. Advanced drivers and weld-detection circuits are therefore necessary to verify the physical state of the contacts and prevent dangerous faults.

Control Strategy

The control strategy of the developed AC Level-2 charging system focuses on ensuring safe, efficient, and intelligent operation throughout the entire charging process. At the core of the approach is the standardized control pilot signaling method defined by IEC 61851 and SAE J1772, which establishes communication between the electric vehicle and the charger using a 1 kHz PWM signal. This signal allows the vehicle to determine whether the charger is connected, ready to supply power, or currently delivering charge, while its duty cycle specifies the maximum charging current permitted by the system. This standardized communication ensures full compatibility across a wide range of electric vehicles regardless of manufacturer. Alongside communication, the system continuously monitors residual current to maintain user safety and prevent dangerous fault conditions. A fluxgate sensor detects both AC and DC leakage values, and if predefined thresholds are exceeded, the controller immediately de-energizes the relays to disconnect the power path and eliminate the hazard. Relay and contactor operation is also optimized through controlled activation using a high pull-in current for quick switching and a reduced holding current to minimize heat generation and energy waste. Additionally, a weld-detection mechanism verifies whether the relay contacts physically opened or closed as expected, preventing scenarios where a mechanical fault could keep the system permanently energized. To enhance system reliability during supply fluctuations or grid failures, a dedicated supercapacitor backup unit provides temporary power to the controller and safety circuitry, allowing the system to release relays, update the pilot communication state, and complete a controlled shutdown. Altogether, this control strategy combines smart communication, real-time protection, efficient hardware operation, and fail-safe behavior, resulting in a robust charging system suitable for modern electric vehicle infrastructure.

Control Pilot Communication

The charger uses a standardized pilot signal to communicate with the electric vehicle, following IEC 61851 and SAE J1772 requirements. A 1 kHz PWM signal is applied to the control pilot line, and the vehicle interprets the voltage level and duty cycle to determine the current charging

state. The duty cycle of the pilot waveform conveys the maximum current that the charger can safely provide, while different voltage levels represent plug connection, readiness to charge, charging in progress, or error conditions. This ensures that the system remains fully compatible with a wide range of EV models regardless of manufacturer.

Residual Current Monitoring

To guarantee user and system safety, the charger continuously monitors for electrical leakage that may arise from insulation failure, wiring damage, or hardware aging. A fluxgate-based residual current detection circuit is used to sense both AC and DC leakage, as DC currents may pass undetected by traditional protection devices. If the detected leakage exceeds the allowable thresholds, the controller immediately shuts down the charging process by opening the relays and isolating the vehicle from the grid, preventing electric shock or equipment failure.

Relay Operation and Weld Detection

The relays responsible for connecting and disconnecting the vehicle from the power supply are controlled using a dual-current approach. A high pull-in current ensures rapid and firm contact closure during activation, while a reduced holding current minimizes heating and energy loss during steady operation. Since relays can become welded due to electrical arcing or mechanical fatigue, the system includes a weld-detection mechanism that verifies whether contacts have physically opened or closed. If a relay fails to switch as commanded, the system identifies the fault and prevents unsafe continuous charging.

Backup Power Management

The charging controller must remain functional even during sudden loss of grid power to ensure a safe shutdown process. To achieve this, the system incorporates a supercapacitor-based backup power supply that stores enough energy to support critical circuits for a short duration. When a power interruption occurs, the stored energy allows the controller to release relays, disengage plug locking mechanisms, update the pilot signal to a safe state, and complete system shutdown without leaving the vehicle or user at risk.

Simulation Setup

To evaluate the performance of the charging system, a simulation model is created that represents the major power-processing blocks found in real hardware. The simulation begins with an AC input source representing grid voltage, typically ranging from 85 V to 460 V RMS. This input is fed to an isolated AC-DC converter modeled as a flyback power stage, which produces regulated output voltages such as +12 V, +14 V, and –14 V. These intermediate supply rails are further stepped down by DC-DC converters and linear regulators to obtain logic-level voltages like 5 V and 3.3 V required for the controller, relay driver, and sensing circuits. A

supercapacitor backup module is integrated into the simulation to provide temporary energy storage. During normal operation, the capacitor remains charged to approximately 7.5–7.8 V. When the main power supply is interrupted, the stored energy supports critical operations for up to three seconds, ensuring that relays disconnect safely and pilot signaling returns to an inactive state. The pilot signal interface is also modeled to generate a ±12 V PWM waveform at 1 kHz, simulating the communication between the EVSE and the vehicle. This allows testing of different charging states such as plug-in detection, charging readiness, active charging, and ventilation requirements. Relay drivers, weld detection circuits, and leakage detection blocks are simulated to evaluate their behavior during normal and fault conditions. Leakage faults such as 30 mA AC and 6 mA DC are injected to check whether the system responds by shutting off the relay within acceptable safety limits.

Block Diagram

The block diagram illustrates the difference between AC charging (Level 1 & Level 2) and DC fast charging (Level 3) for electric vehicles. In the AC charging configuration, the power from the electrical grid is supplied as alternating current (AC) to the Electric Vehicle Supply Equipment (EVSE). This unit ensures safe delivery of electricity, manages communication, and applies protection features. The AC power then flows through the charging cable into the vehicle, where the On-Board Charger (OBC) performs AC-to-DC conversion. The converted high-voltage DC is then regulated and stored directly in the battery pack. In this setup, the vehicle is responsible for power conversion, making the on-board charger a key component.

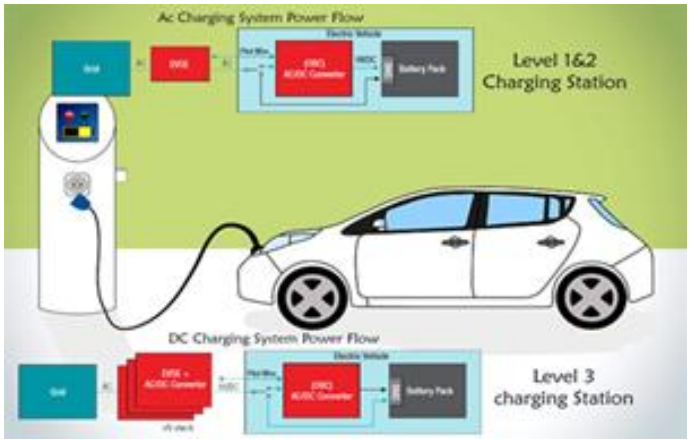


Figure 1: Smart AC Charging Management System for Electric Vehicle

In Level 3 DC fast charging, most power conversion occurs outside the vehicle. The grid feeds AC power into a high-power EVSE that includes its own AC-DC converter. The EVSE converts AC into regulated DC and sends it directly into the vehicle battery using a high-voltage DC connection. Since the vehicle does not need to perform AC-DC conversion, charging is much

faster, and the onboard charger is bypassed. Both charging types rely on a pilot communication wire to exchange information such as maximum current, presence detection, and error signaling. AC charging is slower but lower cost, while DC charging delivers rapid high-power charging suitable for long trips and commercial infrastructure as shown in Figure 1.

Simulation Configuration

The charging controller model was evaluated using a detailed simulation environment that represents the real operating conditions of an AC Level-2 EV charging system. The input stage was supplied with an AC voltage range between 85 V and 460 V at either 50 or 60 Hz to test low-line, nominal, and high-line performance. An isolated flyback converter generated the auxiliary output rails of +12 V, +14 V, and –14 V, which were then stepped down through point-of-load DC-DC converters to produce regulated logic voltages of 5 V, 3.3 V, and 1.8 V for the controller and sensing circuits. A supercapacitor module was incorporated and charged to approximately 7.5–7.8 V, providing emergency hold-up power for around three seconds during supply loss. The pilot signaling system was simulated using a ±12 V, 1 kHz PWM waveform and tested under operational states such as plug-in detection (State A), ready-to-charge (State B), and active charging (State C). Relay actuation and weld detection circuits were analyzed under both normal operation and simulated failure conditions. To validate electrical safety, AC leakage of 30 mA and DC leakage of 6 mA were injected into the system to confirm proper triggering of the residual-current protection mechanism.

Simulation

The simulation demonstrated that the auxiliary power supply maintained stable voltage regulation within ±5% under varying load and line conditions. The supercapacitor-based power reserve successfully delivered approximately 7.5 W for nearly three seconds, allowing the system to disengage relays and complete a safe shutdown when the main supply was removed. The pilot signal behaved as expected, accurately transitioning between IEC 61851/SAE J1772 states, while the PWM duty cycle correctly represented different allowable charging current levels. The relay driver achieved fast engagement using high inrush current and then switched to a lower holding current, which minimized heating and improved energy efficiency. Weld-detection logic reliably identified relay contacts that failed to open during simulated fault conditions. Residual current monitoring detected both AC and DC leakage within the required response time, initiating immediate power cut-off to protect the user and the vehicle. Overall system efficiency was measured at approximately 85%, with standby consumption maintained below 500 mW, confirming that the design meets modern low-power, high-safety EV charging requirements.

Results and Analysis:

The simulation results confirm that the proposed AC Level-2 electric vehicle charging system operates reliably across a wide range of practical conditions. The auxiliary power supply demonstrated stable regulation, maintaining output voltages within ±5% tolerance, even as the input voltage varied from 85 V to 460 V. This shows that the isolated flyback converter and subsequent DC regulation stages are capable of handling fluctuating grid conditions without degrading performance. The supercapacitor backup module provided approximately 7.5 watts of energy for nearly three seconds during simulated mains failure, giving the controller sufficient time to disengage relays, shift the pilot signal to a passive safe state, and ensure an orderly system shutdown. The control pilot communication behaved accurately, interpreting PWM duty cycles according to the IEC 61851 and SAE J1772 charging states, and correctly shifting between states such as vehicle detection, charging readiness, and active charging. Relay performance also met expectations; high pull-in current enabled fast connection while reduced holding current minimized heat buildup and power consumption during steady operation. The weld-detection feature accurately identified conditions where relay contacts refused to open, preventing potentially dangerous continuous power delivery. The residual current detection system successfully sensed both AC leakage at 30 mA and DC leakage at 6 mA, triggering an immediate relay disconnect to protect users and equipment. Overall, the system achieved high operational efficiency of around 85%, with standby consumption remaining below 500 mW, demonstrating that the design delivers strong energy efficiency, reliable communication, and comprehensive protection suitable for modern EV charging

The developed AC Level-2 charging controller successfully delivers stable and regulated output voltages from the auxiliary power supply, ensuring consistent operation of the control, sensing, communication, and protection circuits. During testing, the system demonstrated ultra-low standby power consumption of less than 500 mW, confirming high efficiency even when the charger is not actively supplying energy to the vehicle. The supercapacitor backup unit provided approximately 7.5 W of temporary power for nearly three seconds when the main supply was removed, allowing the controller to disengage relays, revert the pilot signal to a safe condition, and complete a controlled shutdown without user risk. The relay driver operated as expected, offering fast pull-in activation followed by reduced holding current, and the weld-detection mechanism accurately identified situations where contacts failed to open properly. Communication through the ±12 V pilot signal matched all expected IEC 61851 and SAE J1772 charging states, enabling the charger to detect vehicle presence, readiness, and active charging modes. Finally, the residual current detection system responded correctly to both 30 mA AC and

6 mA DC leakage faults, ensuring rapid isolation of the power path to protect both users and the vehicle. Overall, the system output confirms reliable power delivery, strong safety performance, and standards-compliant operation.

Conclusions:

The development and simulation of the AC Level-2 electric vehicle charging controller demonstrate a reliable, efficient, and standards-compliant system suitable for modern EV charging needs. The design successfully integrates stable isolated power conversion, low standby consumption, and intelligent control features that ensure safe and dependable operation under various grid and load conditions. Through standardized ±12 V pilot communication, the system accurately interprets vehicle states and charging limits as defined by IEC 61851 and SAE J1772, ensuring compatibility with a wide range of electric vehicles. Safety mechanisms, including fluxgate-based residual current detection and relay weld verification, operated effectively in response to fault scenarios, providing rapid isolation during both AC and DC leakage faults. The inclusion of a supercapacitor backup system allowed safe shutdown and relay disengagement during sudden power loss, enhancing system resilience and operational security. Overall, the simulation results validate that the charger design meets key performance targets in terms of efficiency, reliability, user safety, and communication accuracy. With further hardware prototyping, electromagnetic compliance testing, and long-term field assessment, this system has strong potential for deployment in real charging networks, contributing to the expanding infrastructure required for widespread EV adoption.

Future Scope:

- The proposed AC Level-2 charging controller can be further enhanced in several meaningful directions to meet the evolving demands of electric vehicle infrastructure. One major area of development is the integration of smart grid and vehicle-to-grid (V2G) capability, which would allow the charger not only to draw power from the grid but also return stored energy from the vehicle during peak demand periods, improving energy management and grid stability.
- The system can also benefit from more advanced digital signal processing and machine learning techniques to improve leakage detection, fault prediction, and maintenance scheduling, making the charger more autonomous and self-diagnostic
- The adoption of new power semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) could significantly increase power efficiency, reduce size, and lower heat losses, enabling more compact and lightweight designs.

References:

1. Sivanadipatham, C. S., Singh, A. K., Kumar, P., & Singh, S. N. (2025). A comprehensive decentralized control framework for balanced and reliable residential EV charging. *IEEE Transactions on Transportation Electrification*.
2. Naidu, P. A., Singhal, A., & Panigrahi, B. K. (2025). An equity-aware residential EV charging control. *IEEE Transactions on Smart Grid*.
3. Gross, O. (2025). Vehicle and infrastructure integration. In *Electric vehicle batteries: From sourcing to second life and recycling* (pp. 83–124).
4. Arulvendhan, K., *et al.,* (2024). Primary side hybrid reconfigurable compensation for wireless EV charging with constant current/constant voltage control. *IEEE Access, 12*, 149,960–149,976.
5. Chaurasiya, S., & Singh, B. (2023). A hybrid synergetic control for 3-φ VSC & 3L-ANPC DC-DC stage for off-board/portable EV charger. In *IEEE International Conference on Energy Technologies for Future Grids (ETFG)* (pp. 1–5). IEEE Xplore.
6. Park, K., Jang, D., Kim, S., Lim, Y., & Lee, J. (2023). A grid-friendly electric vehicle infrastructure: The Korean approach. *IEEE Power and Energy Magazine, 21*(6), 28–37.
7. Texas Instruments. (2022). *AC Level 2 charger platform reference design (TIDA-010239)*.
8. Kazemtarghi, A., Chandwani, A., Ishraq, N., & Mallik, A. (2022). Active compensation-based harmonic reduction technique to mitigate power quality impacts of EV charging systems. *IEEE Transactions on Transportation Electrification, 9*(1), 1629–1640.
9. SAE International. *SAE J1772: Electric vehicle and plug-in hybrid electric vehicle conductive charge coupler*.
10. IEC. *IEC 61851 electric vehicle conductive charging system*.
11. Related academic works on EVSE standby efficiency, RCD methods, and contactor safety.

CLIMATE-RELATED HEALTH ISSUES: HEAT, AIR QUALITY AND PHYSIOTHERAPY MANAGEMENT

Sanhita Sengupta*[1] and Sonia Gupta[2]

[1]Department of Allied Health Sciences,

Brainware University, Barasat, West Bengal, 700125

[2]Department of Physiotherapy,

Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, 244102

*Corresponding author E-mail: sas.ah@brainwareuniversity.ac.in

Abstract:

Climate change has emerged as a critical determinant of global health, with rising temperatures and deteriorating air quality contributing to increased morbidity and mortality. These environmental shifts disproportionately affect vulnerable populations, including older adults, individuals with chronic cardiopulmonary disease, children, outdoor workers, and socioeconomically disadvantaged communities. This chapter examines the physiological mechanisms and health consequences of heat stress and air pollution, highlighting their impact on physical function, exercise tolerance, and rehabilitation outcomes. It underscores the expanding role of physiotherapists in prevention, clinical management, patient education, and sustainable healthcare delivery. Evidence-based strategies such as exercise modification, hydration protocols, heat acclimatization, respiratory physiotherapy techniques, pulmonary rehabilitation, environmental monitoring, and telehealth are presented to support safe and effective care during periods of extreme heat or poor air quality. The chapter further emphasizes health equity, interdisciplinary collaboration, and physiotherapy's potential contribution to climate mitigation through low-carbon clinical practices. As climate-related health challenges intensify, physiotherapists must integrate environmental considerations into assessment, treatment planning, and public health advocacy to safeguard patient well-being and promote resilient healthcare systems.

Keywords: Climate Change, Heat Stress, Air Pollution, Physiotherapy Management, Environmental Health, Rehabilitation Safety.

Introduction:

Climate change represents one of the most pressing public health challenges of the 21st century, profoundly affecting human health through multiple interconnected pathways. Rising global temperatures, deteriorating air quality, and increasingly frequent extreme weather events are

creating novel health challenges that demand adaptive responses from healthcare professionals, including physiotherapists [1,2].

Physiotherapists occupy a unique position within the healthcare system, working at the intersection of prevention, rehabilitation, and health promotion. As environmental factors increasingly influence patient health outcomes, physiotherapists must adapt their clinical practice to address climate-related health issues while simultaneously contributing to climate change mitigation efforts. This chapter explores the mechanisms through which heat stress and air pollution affect human health, examines vulnerable populations, and provides evidence-based physiotherapy management strategies for these emerging challenges.

Heat-Related Health Issues:

Physiological Mechanisms of Heat Stress

Heat stress occurs when the body's thermoregulatory mechanisms become overwhelmed, unable to maintain core temperature within the normal range of 36.5-37.5°C. During passive heat exposure, the cardiovascular system undergoes significant adjustments, including increases in cardiac output through elevations in heart rate and cardiac contractility, as well as increases in sympathetic activity necessary to reduce blood flow from noncutaneous regions [3]. When these compensatory mechanisms fail, individuals may progress through a continuum of heat-related illnesses, from heat cramps and heat exhaustion to potentially fatal heat stroke.

Recent meta-analytic evidence has demonstrated that a 1°C increase in ambient temperature is associated with a 2.1% increase in cardiovascular disease-related mortality, with the highest specific disease risk observed for stroke and coronary heart disease [1]. Median elevations in core temperature and heart rate from baseline to end-exposure during heat stress are approximately 0.9°C and 27 beats/min, respectively [4]. This additional cardiovascular burden significantly elevates mortality risk in individuals with pre-existing cardiovascular conditions, particularly during heat waves.

The cardiovascular strain during heat exposure is particularly pronounced in older adults. Individuals with impaired heat dissipating mechanisms, including those with impaired thermoregulatory and cardiovascular responses to heat stress such as the elderly, individuals with various diseases, and those taking certain medications, have a greater risk for heat-related morbidity and mortality [3,5]. During the 1995 Chicago heat wave and 2003 French heat wave, excess deaths occurred predominantly in older individuals and were overwhelmingly cardiovascular in origin [5].

Impact on Physical Function and Rehabilitation

Heat significantly reduces exercise tolerance through multiple mechanisms. Prolonged high-intensity exercise is markedly impaired by increases in the severity of the thermal environment, characterized by exacerbated development of whole-body hyperthermia and consequent reduction in time to exhaustion [6]. Maximal aerobic power, a key determinant of endurance performance, is also compromised under heat stress in line with the severity of environmental conditions and initial thermal strain [6].

For physiotherapy patients undergoing rehabilitation, these limitations necessitate careful modification of treatment protocols during periods of elevated temperature. Patients with cardiovascular disease, diabetes, respiratory conditions, arthritis, and those taking certain medications (including beta-blockers, diuretics, and anticholinergics) face heightened vulnerability to heat-related complications during exercise.

Vulnerable Populations

Certain populations demonstrate increased susceptibility to heat-related health issues. Research has established that heat exposure leads to elevated risk of morbidity and mortality for women, people 65 years and older, individuals living in tropical climates, and those in countries of lower-middle income [1]. Heatwaves are significantly associated with a 17% increase in risk of mortality, with increasing heatwave intensity associated with increasing risk [1].

Children are vulnerable because of their less developed thermoregulatory systems and greater fluid requirements. Outdoor workers and athletes encounter prolonged heat exposure, increasing their risk of heat stress, dehydration, and associated injuries requiring physiotherapy intervention.

Air Quality and Respiratory Health:

Air Pollution as a Public Health Crisis

Air pollution represents a global health emergency with profound implications for respiratory health. Over 90% of the global population currently resides in areas where environmental air pollution is considered excessive, with adverse effects ranging from acute airway irritation to complex immunomodulatory alterations [7]. Exposure to increased ambient PM2.5 or NO2 presents an additional risk factor for incident adult asthma, although high heterogeneity among studies warrants caution in interpretation [8].

A comprehensive mapping review of 240 systematic reviews and meta-analyses confirmed that air pollution has harmful effects on health, with the most commonly investigated health outcome types being respiratory (mainly asthma and COPD) followed by cardiovascular outcomes (mainly stroke) [9]. Common airborne pollutants such as particulate matter, ozone, and oxidizing

gases stimulate respiratory inflammation, cilia dysfunction, airway remodeling, and respiratory symptoms such as cough [7].

Mechanisms of Air Pollution-Induced Respiratory Damage

Air pollution contributes to respiratory disease through several interconnected mechanisms. Fine particulate matter (PM2.5) penetrates deep into the respiratory system, triggering oxidative stress and inflammatory responses. Environmental air pollution presents a considerable risk to global respiratory health, and if critical levels are exceeded, inhaled pollutants can lead to the development of respiratory dysfunction and provoke exacerbation in those with pre-existing chronic respiratory disease [7].

Studies have demonstrated that exposure to air pollutants is associated with impaired lung development, increased risk for respiratory tract infection, and increased prevalence of and morbidity attributable to asthma and chronic obstructive pulmonary disease [10]. Research indicates that air pollution is linked to more than 7 million premature deaths globally every year [10].

The Exercise Paradox in Polluted Environments

A critical challenge emerges when considering physical activity in polluted urban environments. While regular exercise provides substantial health benefits, exercising in polluted air increases pollutant inhalation due to higher respiratory rates and deeper breathing patterns. Recent research demonstrates that people breathe in more pollutant particles when exercising, possibly because of increased ventilation and breathing through the mouth rather than the nose during physical activity [11].

However, epidemiological studies generally show that the positive chronic health effects of physical activity persist, especially when pollution levels are low and moderate [11]. Large cohort studies have found that being physically active at least twice a week was associated with decreased risk of incident ischemic heart disease among subjects exposed to high levels of PM2.5 and PM10 [12]. Physical activity attenuates air pollution-induced cardiovascular health risks, with evidence showing an inverse interaction effect between physical activity and particulate matter exposure on cardiovascular disease risk [12,13].

The available evidence indicates that for most people, the long-term benefits of regular physical activity outweigh the possible risks of experiencing adverse symptoms from undertaking physical activity during short-term periods of elevated air pollution [14]. However, this balance shifts during periods of exceptionally poor air quality, when outdoor exercise may pose more risk than benefit.

Physiotherapy Management Strategies:

Heat-Related Illness Management

Physiotherapists play a crucial role in helping patients safely maintain physical activity and rehabilitation goals despite heat challenges. Management strategies must address both prevention and adaptation through evidence-based interventions.

Exercise Modification During Heat Exposure

Key strategies for managing exercise during elevated temperatures include:

Timing Optimization: Schedule outdoor activities and exercise sessions during cooler parts of the day, typically early morning or evening hours. This simple modification can significantly reduce heat stress exposure.

Intensity Adjustment: Reduce exercise intensity during hot weather, using perceived exertion scales rather than fixed heart rate targets, as heart rate increases with temperature independent of exercise intensity. Consider implementing interval training that allows for recovery periods.

Hydration Protocols: Implement structured hydration strategies before, during, and after exercise. Pre-exercise hydration should begin several hours before activity. During exercise, fluid intake should aim to replace sweat losses, typically 400-800 mL per hour depending on individual factors and environmental conditions.

Cooling Strategies: Incorporate active cooling techniques including cold water ingestion, application of cold towels, use of cooling vests, and access to air-conditioned recovery spaces. Pre-cooling before exercise and per-cooling during activity breaks can extend safe exercise duration.

Heat Acclimatization: For patients who must exercise in heat, implement gradual heat acclimatization protocols. Heat acclimatization induces physiological adaptations that improve thermoregulation, attenuate physiological strain, reduce the risk of serious heat illness, and improve aerobic performance [15]. The adaptations include improved sweating, improved skin blood flow, lowered body temperatures, reduced cardiovascular strain, improved fluid balance, altered metabolism, and enhanced cellular protection [15].

Generally, athletes can fully heat acclimate with 10 consecutive days of exercise for 90 minutes in appropriate heat conditions [16]. Evidence suggests that controlled hyperthermia regimens where a target core temperature is maintained enable more rapid and complete adaptations relative to traditional constant work rate exercise heat acclimation regimens [15]. Heat acclimatization benefits may be retained for 1-2 weeks, and adaptation decay can be minimized through intermittent exercise-heat exposure [17,18].

Environmental Monitoring and Patient Education

Physiotherapists should educate patients about recognizing early signs of heat-related illness, including unusual fatigue, dizziness, nausea, headache, rapid heartbeat, and altered mental status. Patients should understand when to stop activity and seek cooling. Encourage use of weather monitoring apps and heat alert systems to inform daily activity decisions.

For patients with chronic conditions, physiotherapists should collaborate with physicians to review medications that may impair thermoregulation or increase heat sensitivity. Alternative indoor exercise options should be developed for use during extreme heat periods, ensuring rehabilitation continuity without compromising safety.

Air Quality Management in Respiratory Health:

Assessment and Monitoring

Physiotherapists working with patients affected by air pollution should conduct comprehensive respiratory assessments including lung function testing (spirometry), symptom evaluation, exercise capacity measurement, and quality of life assessment. Regular monitoring allows for detection of pollution-related exacerbations and timely intervention adjustment.

Patients should be educated about air quality indices and encouraged to check daily air quality reports. When air quality is poor (typically when Air Quality Index exceeds 100 for sensitive groups), outdoor activities should be modified or relocated indoors.

Respiratory Physiotherapy Interventions

Specific physiotherapy interventions have demonstrated efficacy in managing respiratory health in the context of air pollution:

Breathing Exercises: Diaphragmatic breathing, pursed-lip breathing, and breathing control techniques help improve respiratory efficiency, reduce dyspnea, and enhance gas exchange. These techniques are particularly valuable for patients with COPD and asthma experiencing pollution-related symptom exacerbation.

Inspiratory Muscle Training (IMT): Targeted strengthening of inspiratory muscles through resistive breathing devices improves respiratory muscle strength and endurance, enhancing patients' ability to cope with increased respiratory demands during polluted air exposure.

Airway Clearance Techniques: For patients with increased mucus production related to air pollution exposure, techniques including postural drainage, percussion, vibration, and active cycle of breathing facilitate secretion clearance and prevent secondary complications.

Pulmonary Rehabilitation: Comprehensive pulmonary rehabilitation programs provide substantial benefits for patients with chronic respiratory diseases. There is level 1 evidence supporting the benefits of pulmonary rehabilitation for chronic obstructive pulmonary disease (COPD), including improved exercise capacity, reduced dyspnea, enhanced health-related

quality of life, and reduced hospital admissions [19]. Pulmonary rehabilitation is defined as a comprehensive intervention based on thorough patient assessment followed by patient-tailored therapies that include exercise training, education, and behavior change, designed to improve the physical and psychological condition of people with chronic respiratory disease [19,20].

Studies have Proved that pulmonary recuperation has salutary goods in cases with asthma at any stage of the complaint, perfecting exercise capacity, asthma control, and quality of life and reducing gasping, anxiety, depression, and bronchial inflammation [21]. Exercise training is a largely effective intervention in COPD cases to ameliorate exercise capacity and health status [20]. Exercise tradition in weakened surroundings When defining exercise for cases living in areas with air pollution challenges Inner Alternatives Prioritize inner exercise installations with acceptable ventilation and air filtration systems. numerous installations now feature HEPA filtration systems that significantly reduce inner air pollution. Route Selection When out-of-door exercise is necessary, advise cases to choose routes down from high- business roads, as business-related air pollution is particularly dangerous. Parks and green spaces generally have lower pollutant attention. Timing Considerations Air pollution situations vary throughout the day. In numerous civic areas, morning hours before rush hour and late evening have lower pollution situations. Ozone situations peak in the autumn, so morning exercise may be preferable in ozone-affected areas. Intensity Management During poor air quality days, reduce exercise intensity to minimize respiratory rate and contaminant inhalation. Although advanced intensity exercise leads to an increase in the gobbled cure of adulterants for a given distance travelled, the acute goods of diesel exhaust air pollution do n't appear to be more pronounced at advanced intensities[11]. Low- to-moderate intensity exercise still provides health benefits while reducing exposure. Protective Equipment While substantiation regarding mask effectiveness for air pollution during exercise is mixed, duly fitted N95 or KN95 respirators can reduce particulate matter exposure. still, masks increase breathing resistance and may not be suitable for all cases, particularly those with being respiratory concession. Masks may have salutary goods on certain issues at low intensity exercise in pollution with significant situations of patches, but more study is needed in realistic conditions [11]. Integrating Telehealth for Climate-flexible Care Telehealth has surfaced as a climate- flexible result in activity practice. Virtual consultations reduce patient trip- related carbon emigrations while maintaining care durability. During extreme rainfall events heat swells, poor air quality days, cataracts, or backfires telehealth enables physiotherapists to continue patient care without taking dangerous trip. Telehealth is particularly precious for follow- up assessments during environmental hazards, remote exercise instruction and monitoring, case education about managing conditions during climate events, reviewing and conforming home exercise programs, furnishing cerebral support during climate- related stress

exploration indicates that cases respond well to telehealth activity, with similar issues to in-person care for numerous conditions. Case Education and tone- operation Empowering cases to manage their health in the environment of climate challenges is essential for sustainable healthcare. Physiotherapists should educate cases about Environmental Monitoring How to pierce and interpret rainfall vaticinations, heat warnings, and air quality indicators Symptom Recognition Early advising signs of heat- related illness and pollution- related respiratory torture tone- Care Strategies Hydration, apparel choices, timing of conditioning, inner exercise druthers Emergency Planning What to do when symptoms worsen, when to seek medical care Long- term adaption Developing sustainable exercise routines that regard for environmental variability preventative Approaches and Health Promotion Physiotherapy's part extends beyond treating climate- related health issues to forestalment and health creation. Promoting active transportation walking and cycling, when safe to do so provides binary benefits bettered individual health and reduced environmental impact through dropped vehicle emigrations. Physiotherapists can endorse for creation and preservation of safe out-of-door exercise spaces with acceptable shade and ventilation, development of accessible inner exercise installations with air quality controls, public education about exercise revision during extreme rainfall, policy changes supporting active transportation structure, integration of climate health considerations into community health planning, Vulnerable Populations Special Considerations habitual Disease Management Cases with pre-existing habitual conditions bear personalized approaches. Those with arthritis may witness increased common pain during temperature axes or barometric pressure changes. Physiotherapists should acclimatize treatment plans consequently, maybe emphasizing water-grounded exercise during heat swells (buoyancy reduces common stress while water provides cooling) or inner resistance training during poor air quality ages.

Patients with cardiovascular disease face compounded risks from both heat and air pollution. These individuals require conservative exercise prescription during environmental stress, with particular attention to symptoms, blood pressure monitoring, and medication effects. Close collaboration with cardiologists ensures safe, effective rehabilitation.

Pediatric Considerations

Children's developing respiratory systems and higher breathing rates make them particularly vulnerable to air pollution. Youth groups are in the growth period, and their respiratory system is not yet mature; hence, they are more susceptible to atmospheric particulates than adults [22]. Pediatric physiotherapists should educate families about minimizing outdoor play during poor air quality, choosing play locations away from traffic, and monitoring children for respiratory symptoms. For children with asthma, air pollution represents a significant exacerbation trigger requiring proactive management.

Elderly Patients

Age-related declines in thermoregulation, cardiovascular reserve, and medication effects increase elderly patients' vulnerability to heat. Many elderly individuals have reduced thirst perception, increasing dehydration risk. Physiotherapists working with geriatric populations should implement simplified hydration protocols, heat avoidance strategies, and regular monitoring during warm weather. Social isolation in elderly populations may prevent awareness of heat warnings; physiotherapists may need to coordinate with social services to ensure vulnerable elderly patients receive support during extreme weather events.

Addressing Health Equity

Climate change disproportionately affects vulnerable and marginalized populations who often have limited resources to adapt to environmental challenges. Those living in poverty may lack access to air conditioning, have housing with poor insulation and ventilation, live in areas with higher air pollution exposure, and have limited access to healthcare services.

Physiotherapists must recognize these equity considerations when developing treatment plans and community interventions. Strategies might include:

- Partnering with community organizations to provide exercise programs in accessible, climate-controlled spaces
- Developing low-cost cooling strategies for home use
- Advocating for policies addressing environmental justice
- Considering transportation barriers when scheduling appointments
- Utilizing telehealth to improve access for underserved populations

The Role of Physiotherapy in Climate Mitigation

Beyond adapting practice to address climate health impacts, physiotherapists can contribute to climate change mitigation. The healthcare sector generates significant greenhouse gas emissions. Physiotherapy, with its emphasis on non-pharmacological, non-surgical interventions, represents a potentially low-carbon healthcare approach.

Strategies for reducing physiotherapy's environmental footprint include:

- Maximizing telehealth when clinically appropriate
- Promoting active transportation for patients and staff
- Implementing energy-efficient clinic operations
- Reducing single-use equipment and supplies
- Advocating for sustainable healthcare policies
- Educating patients about the health co-benefits of climate-friendly behaviors

Future Directions and Research Needs

While emerging evidence illuminates the intersection of climate change and physiotherapy practice, significant knowledge gaps remain. Future research should address:

- **Optimal intervention protocols:** Systematic evaluation of exercise modification strategies during different environmental stressors
- **Long-term outcomes:** Studies examining cumulative effects of repeated climate-related health events on patient outcomes
- **Technology integration:** Development and validation of wearable sensors for real-time environmental monitoring and exercise adjustment
- **Comparative effectiveness:** Research comparing outcomes of various adaptation strategies
- **Educational interventions:** Evaluation of climate health education programs for physiotherapy students and practitioners
- **Policy impact:** Assessment of how healthcare policies addressing climate change affect physiotherapy practice and patient outcomes
- **Exercise thresholds:** More research is needed on the exact thresholds of when environmental exposures may be harmful for human health, particularly concerning people with preexisting cardiovascular disease, lung disease, children, and the elderly [12,14].

Conclusion:

Climate change poses significant health risks, requiring physiotherapists to adapt practice to hotter climates and poorer air quality. By modifying exercise programs, monitoring environmental conditions, educating patients, and using technologies like telehealth, physiotherapists can continue delivering safe, effective care. Evidence shows that targeted interventions can prevent heat-related illness, support respiratory health, and maintain physical activity despite environmental challenges. As climate impacts grow, physiotherapists must stay informed, advocate for sustainable healthcare, and integrate environmental considerations into routine practice. Climate-aware physiotherapy is now essential for protecting patient health and promoting resilience in a changing world.

References:

1. Bouchama, A., Abuyassin, B., Lehe, C., *et al.,* (2022). Heat exposure and cardiovascular health outcomes: A systematic review and meta-analysis. *Lancet Planetary Health, 6*(6), e484–e495. https://doi.org/10.1016/S2542-5196(22)00117-6
2. Alyami, M. M., Balharith, F. H., Ravi, S. K., & Reddy, R. S. (2025). Urban air pollution and chronic respiratory diseases in adults: Insights from a cross-sectional study. *Frontiers in Public Health, 13*, 1507882. https://doi.org/10.3389/fpubh.2025.1507882

3. Wilson, T. E., Sauder, C. L., Kearney, M. L., *et al.,* (2016). Human cardiovascular responses to passive heat stress. *Comprehensive Physiology, 6*(3), 1359–1399. https://doi.org/10.1002/cphy.c150051
4. Fisher, J. T., Young, C. N., & Brothers, R. M. (2025). Meta-analysis of heat-induced changes in cardiac function from over 400 laboratory-based heat exposure studies. *Nature Communications, 16*, 2157. https://doi.org/10.1038/s41467-025-57868-6
5. Kenney, W. L., & Munce, T. A. (2014). Invited review: Aging and human temperature regulation. *Journal of Applied Physiology, 116*(9), 1093–1096. https://doi.org/10.1152/japplphysiol.00095.2014
6. Sawka, M. N., Cheuvront, S. N., & Kenefick, R. W. (2021). Exercise under heat stress: Thermoregulation, hydration, performance implications, and mitigation strategies. *Physiological Reviews, 101*(2), 521–589. https://doi.org/10.1152/physrev.00038.2020
7. Wallbanks, S., Griffiths, B., Thomas, M., Price, O. J., & Sylvester, K. P. (2024). Impact of environmental air pollution on respiratory health and function. *Physiological Reports, 12*(16), e16171. https://doi.org/10.14814/phy2.16171
8. Brigham, E., de Hoogh, K., Beelen, R., *et al.,* (2024). Ambient air pollution exposure and adult asthma incidence: A systematic review and meta-analysis. *Lancet Planetary Health, 8*(12), e950–e963. https://doi.org/10.1016/S2542-5196(24)00279-1
9. Dominski, F. H., Lorenzetti Branco, J. H., Buonanno, G., Stabile, L., Gameiro da Silva, M., & Andrade, A. (2021). Effects of air pollution on health: A mapping review of systematic reviews and meta-analyses. *Environmental Research, 201*, 111487. https://doi.org/10.1016/j.envres.2021.111487
10. Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., *et al.,* (2023). Air pollution and respiratory infections: The past, present, and future. *Journal of Thoracic Disease, 15*(3), 1353–1376. https://doi.org/10.21037/jtd-22-1512
11. Koehle, M. S. (2024). Physiological impacts of atmospheric pollution: Effects of environmental air pollution on exercise. *Physiological Reports, 12*(7), e16003. https://doi.org/10.14814/phy2.16003
12. Münzel, T., Hahad, O., Daiber, A., & Lelieveld, J. (2021). Physical activity in polluted air—Net benefit or harm to cardiovascular health? A comprehensive review. *Antioxidants, 10*(11), 1787. https://doi.org/10.3390/antiox10111787
13. Tu, R., Qian, Y., Xu, L., *et al.,* (2020). Interaction effect of air pollution and meteorological factors on cardiovascular disease in elderly people: A time-series analysis in Kunshan, China. *International Journal of Environmental Research and Public Health, 17*(22), 8442. https://doi.org/10.3390/ijerph17228442

14. Committee on the Medical Effects of Air Pollutants. (2025). *Working paper 4: Physical activity and exposure to air pollution*. GOV.UK. Accessed November 2025. https://www.gov.uk/government/publications/advice-given-to-the-air-quality-information-system-aqis-review-steering-group/working-paper-4-physical-activity-and-exposure-to-air-pollution
15. Périard, J. D., Racinais, S., & Sawka, M. N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. *Scandinavian Journal of Medicine & Science in Sports, 25*(Suppl. 1), 20–38. https://doi.org/10.1111/sms.12408
16. Tyler, C. J., Reeve, T., & Cheung, S. S. (2019). Application of evidence-based recommendations for heat acclimation: Individual and team sport perspectives. *Temperature, 6*(1), 37–49. https://doi.org/10.1080/23328940.2018.1516537
17. Lorenzo, S., Halliwill, J. R., Sawka, M. N., & Minson, C. T. (2010). Heat acclimation improves exercise performance. *Journal of Applied Physiology, 109*(4), 1140–1147. https://doi.org/10.1152/japplphysiol.00495.2010
18. Gibson, O. R., James, C. A., Mee, J. A., *et al.,* (2024). Effect of condensed heat acclimation on thermophysiological adaptations, hypoxic cross-tolerance, exercise performance, and deacclimation. *Journal of Applied Physiology, 137*(5), 1224–1238. https://doi.org/10.1152/japplphysiol.00775.2024
19. Spruit, M. A., Singh, S. J., Garvey, C., *et al.,* (2021). Defining modern pulmonary rehabilitation: An official American Thoracic Society workshop report. *Annals of the American Thoracic Society, 18*(5), e12–e29. https://doi.org/10.1513/AnnalsATS.202102-146ST
20. Ries, A. L. (2020). Pulmonary rehabilitation for chronic obstructive pulmonary disease: Highly effective but often overlooked. *Proceedings of the American Thoracic Society, 5*(4), 524–529. https://doi.org/10.1513/pats.200708-123ET
21. Guazzi, M., Dickstein, K., Vicenzi, M., & Arena, R. (2020). Pulmonary rehabilitation and asthma. *Frontiers in Rehabilitation Sciences, 1*, 00003. https://doi.org/10.3389/fresc.2020.00003
22. Chen, Z., Salam, M. T., Eckel, S. P., Breton, C. V., & Gilliland, F. D. (2022). Physical exercise in the context of air pollution: An emerging research topic. *Frontiers in Physiology, 13*, 784705. https://doi.org/10.3389/fphys.2022.784705

PHYTOREMEDIATION AN ECO-FRIENDLY TOOL FOR WASTE WATER MANAGEMENT

Seema Bhagowati

Assam Agricultural University - Horticulture Research Station (AAU-HRS),

Kahikuchi, Guwahati-17, Assam

Corresponding author E-mail: seema.bhagowati@aau.ac.in

Abstract:

In the realm of global water crisis affecting whole world, seeking alternative ways to treat wastewater for recycling is crucial. Using biological methods for wastewater treatment is seen as a green and economical process that will be relevant in the future. Various living organisms, particularly plants, can help to clean pollutants from wastewater including substances like dyes, heavy metals, hydrocarbons, pharmaceuticals, and pesticides found especially in farming areas. Phytoremediation can act as a cost-effective and environmentally friendly technique that uses plants to immobilize, uptake, reduce toxicity, stabilize, or degrade the compounds that are released into the environment from various sources. Studies have shown that heavy metals, organic contaminants, radionuclides, antibiotics, and pesticides can be remediated using plants. Though phytoremediation has been practiced since decades, it is still an emerging technology.

1. Introduction:

Globally, nearly 2 million metric tons of wastewater are dumped into water bodies, particularly affecting poorer nations where surface water bodies receive a significant proportion of untreated industrial effluents and raw sewage (Azizullah *et al.,* 2011) which impacts the water bodies with severe pollution, by enriching wastewater through heavy metals (HMs). It is clear from these challenges that wastewater must be treated before being released into an aquatic environment. Wastewater treatment is an essential concern in order to provide clean drinking water and preserve biodiversity.

For waste water treatment, traditional wastewater treatment methods, such as distillation systems or using physicochemical techniques like ion exchange, adsorption, reverse osmosis, and UV treatment, have been utilized. However, these techniques often generate sludge and are time-consuming, expensive, and inefficient (Ahila *et al.,* 2020).

In recent years, an environmentally friendly technology, phytoremediation, has gained prominence as an alternative for wastewater treatment. Initially explored by Boyd in 1970,

phytoremediation employs selected vascular plants to destroy, extract, or isolate pollutants from polluted environments. Subsequent research by Cowgill and others focused on eliminating HMs from wastewater (Sharma *et al.,* 2024).

Phytoremediation is a wastewater treatment method that uses specific plants to remove, degrade, or stabilize pollutants like heavy metals, nutrients, and organic compounds. This eco-friendly and cost-effective approach utilizes plant mechanisms such as phytoextraction (absorption into plant tissue), rhizofiltration (absorption by roots), phytostabilization (immobilizing contaminants), and phytodegradation (breaking down pollutants). Common plants like water hyacinths, duckweeds, and water lettuce are effective in systems such as constructed wetlands for treating sewage, industrial effluent, and agricultural runoff.

2. Phytoremediation Mechanisms

Phytoremediation is an eco -friendly method for cleaning up contaminated wastewater that relies on various ways by which plants can help in reducing the effects of pollutants. Understanding how these mechanisms work is crucial for improving the effectiveness of phytoremediation techniques. Figure. 1 intricately displays the fundamental mechanisms involved in the process. Various mechanisms involved in phyto remediation are discussed below:

i. Uptake and Accumulation

The initiation of phytoremediation involves the absorption of pollutants by plant roots, functioning as natural filters that selectively draw pollutants from the surrounding water (Abdel-Shafy & Mansour 2018). This process engages physiological mechanisms facilitating the transport of contaminants from water into plant tissues. A thorough examination of factors influencing uptake efficiency becomes crucial for judiciously selecting plant species across phytoremediation applications (Kvesitadze *et al.,* 2015).

ii. Transformation and Detoxification

Subsequent to the absorption of contaminants, plants undergo biochemical processes for the transformation and detoxification of pollutants (Singh & Jain 2003). This involves metabolic activities within plant cells, leading to the conversion of toxic substances into less harmful forms. A thorough investigation into the enzymatic pathways governing this transformation provides insights into the potential of different plant species to detoxify specific contaminants (Jabeen *et al.,* 2009).

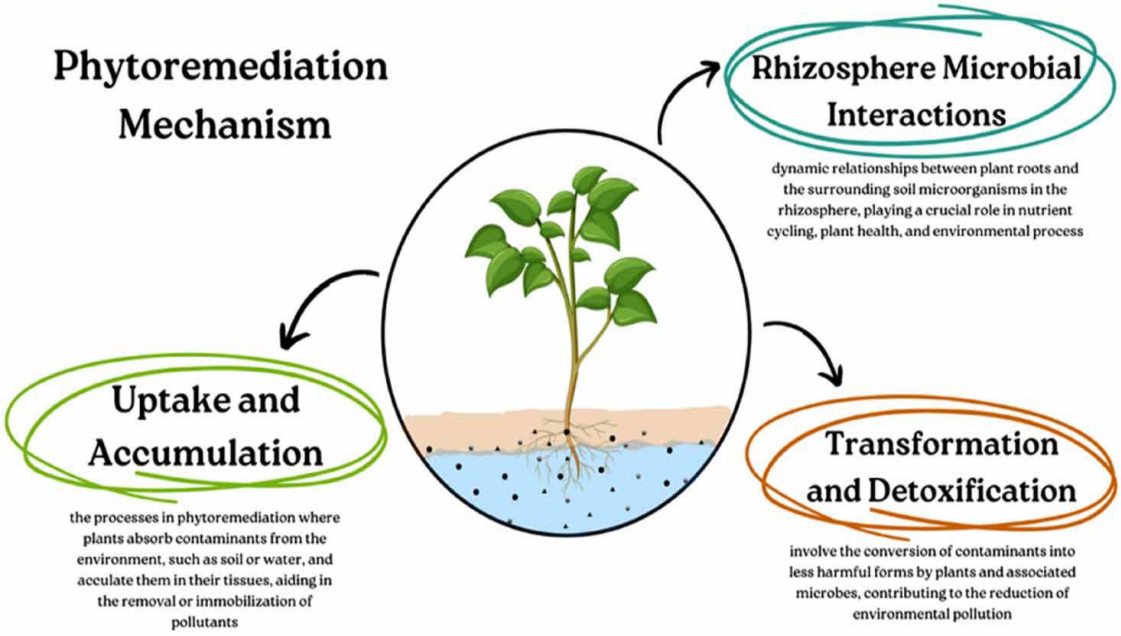


Figure 1: A flowchart of the mechanisms involved in phytoremediation

iii. Rhizosphere Microbial Interactions

The rhizosphere, influenced by root secretions, plays a pivotal role in the phytoremediation process. Microorganisms within this zone actively contribute to contaminant degradation and nutrient cycling. A detailed exploration of interactions between plant roots and rhizospheric microbes offers valuable insights into microbial-assisted mechanisms that enhance the overall efficiency of phytoremediation (Agarwal *et al.,* 2020). Understanding these fundamental phytoremediation mechanisms is vital for the development of sustainable and effective wastewater treatment strategies. Subsequent sections will explore specific phytoremediation types and explore case studies demonstrating the application of these mechanisms in diverse environmental contexts.

3. Types of Wastewater Contaminants

Contamination of water bodies occurs from multiple sources, bringing varieties of harmful substances that negatively affect both the environment and human health. The two primary types of pollutants are inorganic pollutants and organic pollutants.

- **Inorganic pollutants**: Inorganic materials include industrial waste, nutrients, HM, and sediments etc.
- **Organic pollutants:** Organic pollutants in wastewater are carbon-based substances that can harm the environment and human health, originating from sources like domestic waste, industrial processes, and agriculture. Examples include pharmaceutical wastes, dyes, pesticides, petroleum products, and human waste, which can deplete oxygen in water bodies and have toxic effects if not properly treated.

4. Types of Phytoremediation:

The use of plant-based remediation techniques not only addresses environmental pollution but also contributes to sustainable and eco-friendly solutions for managing diverse forms of contaminants in different environments. Different types of phytoremediation are discussed below and the figure 2 several represents different phytoremediation approaches (Sharma et. al, 2024)

i. Phytoextraction:

In phytoextraction plants having ability of heavy metal accumulation are grown in polluted areas and metal-enriched biomass upon maturity are harvested for safe disposal. This method aids in removing contaminants from the soil. The efficacy of phytoextraction depends on the ability of plants to absorb and store metals in their aerial parts, considering metal availability for absorption. Disposal of the heavy metal accumulated biomass is done either through composting or incineration, with limited recycling for further use.

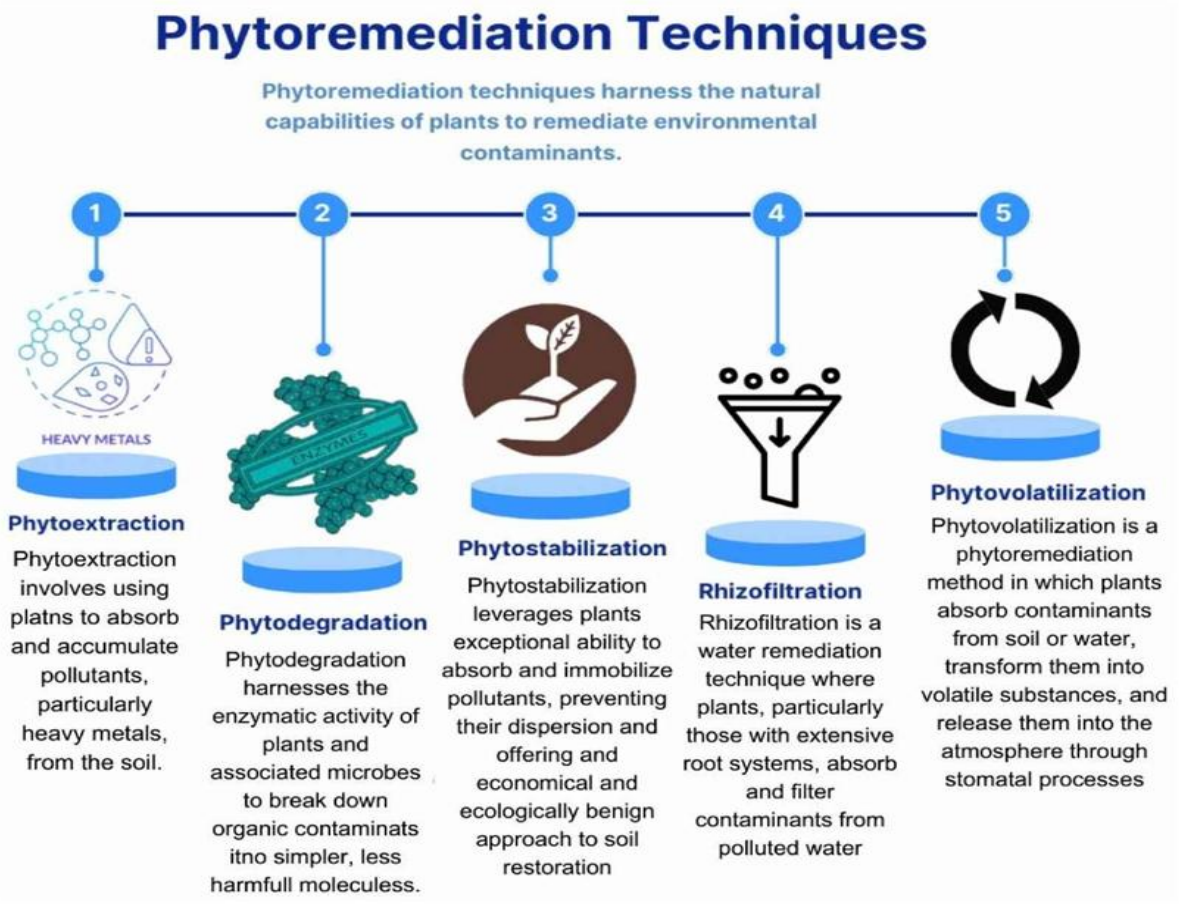


Figure 2. Illustration of phytoremediation techniques

ii. Phytodegradation:

Phytodegradation is the process by which the enzymatic activity of plants and their associated microbes are utilized to convert organic contaminants into simpler molecules. This process relies on plants' capacity to produce necessary enzymes that initiate the breakdown of xenobiotics

(Alkio *et al.,* 2005). The success of phytodegradation depends on combined interactions among soil, water, microbes, and plants, with the plant's role being pivotal in providing a surface area for bacteria colonization around the shoot and root. This, in turn, enhances microbial activity, enabling the breakdown of carbon substrates. Researchers suggest that phytodegradation is applicable in various habitats, encompassing surface and groundwater, soil, as well as river sediments and sludges.

The effectiveness and pertinency of this green remediation approach have been greatly increased by developments in phytodegradation methods. One of the most current developments is the genetically engineered plants that express enzymes that more efficiently degrade a variety of organic contaminants (Rai *et al.,* 2020). For example, plants are able to break down complex organic pollutants like pesticides, medicines, and industrial chemicals since genes encoding for enzymes like laccases, peroxidases, and cytochrome P450 monooxygenases have been inserted into the plants.

iii. Phytostabilization:

Phytostabilization relies on special ability of plant to absorb and store pollutants, which leads to their immobilization or solidification. This approach efficiently hampers the dispersion of pollutants through precipitation, runoff, inhibiting their entry into groundwater and migration to surface soil. Plants selected for phytostabilization exhibit desirable characteristics, such as a robust root system that promotes the adsorption and accumulation of pollutants in tissues. The absorption of pollutants and their conversion into less soluble composites in the rhizosphere further enhances the efficacy of phytostabilization (Materac *et al.,* 2015). Plants with extensive root systems, such as legumes and grasses, are commonly utilized because they aid in immobilizing contaminants. By using this technique, HM bioavailability can be decreased by up to 80% (Ogundola *et al.,* 2022).

iv. Rhizofiltration:

Rhizofiltration demonstrates to be an important technique for dealing surface wastewater resulting from industrial and agricultural activities, where plants play a crucial role in the remediation process. In this method, plants are either exposed to waste water soaked in their roots or submerged in purified water. The efficacy of rhizofiltration depends on selecting plants resistant to low oxygen concentrations, processing a large and rapidly developing root system, yielding substantial biomass, and demonstrating high tolerance to toxic compounds (Materac *et al.,* 2015). According to Raskin & Ensley (2000), the effectiveness of rhizofiltration is proved, demonstrating that plant roots actively absorb contaminants and HMs from their surroundings. Rhizofiltration has proven successful in handling HMs such as Pb, Cu, Co, Cd, uranium (U), and

As, which are often challenging to remove using conventional techniques. This economically viable and ecologically benign approach deploys plant roots to collect and eliminate these HMs from polluted water streams (Srivastava et al). Aquatic plants, such as water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna minor*), are commonly used for the reason that they have great resistance to water contaminants. Plants with enhanced metal accumulation and tolerance have been created through genetic engineering. The efficacy of rhizofiltration has been increased by its combination with other treatment techniques, including built wetlands and bioreactors.

v. Phytovolatilization:

In this method pollutants are converted into hazardous compounds by green plants, utilizing the plant's stomata to release volatile substances into the surrounding environment (Leguizamo *et al.,* 2017). In this technique, plants absorb pollutants from water or soil, converting them into less hazardous forms thereby releasing them into the atmosphere. Plants naturally manage and transport numerous gases, including water vapor (H_2O), carbon dioxide (CO_2), oxygen (O_2), ethylene (C_2H_4), and signaling chemicals (Materac *et al.,* 2015). The volatile organic compounds carrying activation system is triggered throughout the plant on the basis of physiology of the plant and the properties of the contaminant. Phytovolatilization finds regular application in removing organic contaminants such as trichloroethylene (C_2HCl_3), benzene (C_6H_6), nitrobenzene ($C_6H_5NO_2$), phenol (C_6H_5OH), and atrazine ($C_8H_{14}ClN_5$) from soil and water, as well as HMs like Hg, selenium (Se), or As (Wang *et al.,* 2009). Pollutants like Se and Hg are volatilized by plants like mustard and poplar. Under ideal circumstances, this process can volatilize up to 70–80% of certain pollutants. The rate of volatilization differs significantly depending on the kind of plant and surrounding conditions, certain plants can release up to 50 g of Hg per hectare per year. By adding or overexpressing genes linked to the detoxification and emission processes, genetic engineering has been used to improve plants' capacity to volatilize toxins, such as HMs and organic pollutants (Mamun *et al.,* 2024).

5. Selection of Suitable Plants for Wastewater Treatments:

Efficient wastewater treatment through phytoremediation depends on the careful selection of plant species that exhibit specific traits advantageous to the remediation process. For this phytoremediation process three essential aspects are considered in the selection of suitable plants, they are hyperaccumulators, tolerance and adaption, and growth characteristics.

i. Hyperaccumulators: These are accumulator plants, having exceptional capability to collect higher concentrations of metals in their leaves and commonly found in naturally mineralized soils. These hyperaccumulator plants can gather metals without showing any symptoms of

poisoning in their above-ground tissues. These unusual plants are found across various regions, including Europe, North America, New Caledonia, and South Africa, thriving in soils abundant in metal content.

ii. Tolerance and Adaptation: When the concentration of pollutant in wastewater environment increases plants establish their capacity to bear higher level of pollutants and adjust to the prevailing typical conditions. These plants employ sophisticated tolerance strategies to fight against the associated toxicity when HM ions permeate the cellular domain. Detoxification becomes critical when excess HM ions accumulate within the cytosol, compelling plants to mitigate their toxic effects. This complex procedure comprises chelation, where HM ions form complexes with ligands, minimising the concentrations of free metal ions to minimum level.

iii. Growth Characteristics: In case of phytoremediation, the growth characteristics of selected plants appears as key determinants of wastewater treatment efficiency. Factors like rapid growth (Abdelkrim *et al.,* 2019), extensive root systems (Abdelhameed & Metwally 2019), and significant biomass yield are contributory traits to the effective removal of pollutants (Aken 2008). These required growth features not only enhance the complete process of phytoremediation but also ease cost-effective and sustainable approaches to wastewater treatment. A thorough understanding and effective utilization of the growth characteristics specific to each plant species become imperative for optimizing their potential in attaining success in environmental cleanup process. The ability of hyperaccumulator plants to flourish under elevated levels of HM can be attributed to multiple biochemical pathways that help maintain lower metal concentrations in the cytoplasm as compared to the soil, safeguarding cytoplasmic organelles from the toxic effects of HMs (Nedjimi, 2009). During their normal growth and reproduction, hyperaccumulator plants effectively accumulate large quantities of HMs in their above-ground parts with some exhibiting the capacity to accumulate non-essential HMs, such as Pb, Ag, Cd, and Hg, which lack functions (Nedjimi & Daoud, 2009).

Conclusion:

Phytoremediation is an important and sustainable wastewater treatment method consisting effective techniques such as phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization. Among these techniques phytoextraction is a promising method which uses hyperaccumulator plants for successful treat HM contamination. The use of plants in remediation strategies– especially when it comes to techniques like phytoextraction– offers hope for a cleaner and greener future and makes a significant contribution to the discussion about sustainable wastewater treatment methods.

References:

1. Abdelhameed, R. E., & Metwally, R. A. (2019). Alleviation of cadmium stress by arbuscular mycorrhizal symbiosis. *International Journal of Phytoremediation, 21*(7), 663–671.
2. Abdelkrim, S., Jebara, S. H., Saadani, O., Chiboub, M., Abid, G., Mannai, K., & Jebara, M. (2019). Heavy metal accumulation in *Lathyrus sativus* growing in contaminated soils and identification of symbiotic resistant bacteria. *Archives of Microbiology, 201*(1), 107–121.
3. Abdel-Shafy, H. I., & Mansour, M. S. M. (2018). Phytoremediation for the elimination of metals, pesticides, PAHs, and other pollutants from wastewater and soil. In V. Kumar, M. Kumar, & R. Prasad (Eds.), *Phytobiont and ecosystem restitution* (pp. 101–136). Springer, Singapore.
4. Agarwal, P., Giri, B. S., & Rani, R. (2020). Unravelling the role of rhizospheric plant–microbe synergy in phytoremediation: A genomic perspective. *Current Genomics, 21*(5), 334–342.
5. Ahila, K. G., Ravindran, B., Muthunarayanan, V., Nguyen, D. D., Nguyen, X. C., Chang, S. W., Nguyen, V. K., & Thamaraiselvi, C. (2020). Phytoremediation potential of freshwater macrophytes for treating dye-containing wastewater. *Sustainability, 13*(1), 329.
6. Aken, B. V. (2008). Transgenic plants for phytoremediation: Helping nature to clean up environmental pollution. *Trends in Biotechnology, 26*(5), 225–227.
7. Alkio, M., Tabuchi, T. M., Wang, X., & Colón-Carmona, A. (2005). Stress responses to polycyclic aromatic hydrocarbons in *Arabidopsis* include growth inhibition and hypersensitive response-like symptoms. *Journal of Experimental Botany, 56*(421), 2983–2994.
8. Azizullah, A., Khattak, M. N. K., Richter, P., & Häder, D. P. (2011). Water pollution in Pakistan and its impact on public health – A review. *Environment International, 37*(2), 479–497.
9. Jabeen, R., Ahmad, A., & Iqbal, M. (2009). Phytoremediation of heavy metals: Physiological and molecular mechanisms. *The Botanical Review, 75*(4), 339–364.
10. Kvesitadze, G., Khatisashvili, G., Sadunishvili, T., & Kvesitadze, E. (2015). Plants for remediation: Uptake, translocation and transformation of organic pollutants. In M. Öztürk, M. Ashraf, A. Aksoy, M. Ahmad, & K. Hakeem (Eds.), *Plants, pollutants and remediation* (pp. 241–308). Springer, Dordrecht.

11. Leguizamo, M. A. O., Gómez, W. D. F., & Sarmiento, M. C. G. (2017). Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands – A review. *Chemosphere, 168*, 1230–1247.
12. Mamun, A. A., Rahman, M. M., Huq, M. A., Rahman, M. M., Rana, M. R., Rahman, S. T., Khatun, M. L., & Alam, M. K. (2024). Phytoremediation: A transgenic perspective in omics era. *Transgenic Research, 33*, 1–20.
13. Materac, M., Wyrwicka, A., & Sobiecka, E. (2015). Phytoremediation techniques in wastewater treatment. *Environmental Biotechnology, 11*(1), 10–13.
14. Nedjimi, B., & Daoud, Y. (2009). Cadmium accumulation in *Atriplex halimus* subsp. *schweinfurthii* and its influence on growth, proline, root hydraulic conductivity and nutrient uptake. *Flora – Morphology, Distribution, Functional Ecology of Plants, 204*(4), 316–324.
15. Nedjimi, B. (2009). Can calcium protect *Atriplex halimus* subsp. *schweinfurthii* against cadmium toxicity? *Acta Botanica Gallica, 156*(3), 391–397.
16. Ogundola, A. F., Adebayo, E. A., & Ajao, S. O. (2022). Phytoremediation: The ultimate technique for reinstating soil contaminated with heavy metals and other pollutants. In V. Kumar, M. P. Shah, & S. K. Shahi (Eds.), *Phytoremediation technology for the removal of heavy metals and other contaminants from soil and water* (pp. 19–49). Elsevier, Amsterdam.
17. Rai, P. K., Kim, K. H., Lee, S. S., & Lee, J. H. (2020). Molecular mechanisms in phytoremediation of environmental contaminants and prospects of engineered transgenic plants/microbes. *Science of The Total Environment, 705*, 135858.
18. Raskin, I., & Ensley, B. D. (2000). *Phytoremediation of toxic metals*. John Wiley & Sons, New Jersey.
19. Sharma, M., Rawat, S., & Rautela, A. (2024). Phytoremediation in sustainable wastewater management: An eco-friendly review of current techniques and future prospects. *AQUA — Water Infrastructure, Ecosystems and Society, 73*(9), 1946–1975.
20. Singh, O. V., & Jain, R. K. (2003). Phytoremediation of toxic aromatic pollutants from soil. *Applied Microbiology and Biotechnology, 63*(2), 128–135.
21. Wang, J., Zhang, C. B., & Jin, Z. X. (2009). The distribution and phytoavailability of heavy metal fractions in rhizosphere soils of *Paulownia fortunei* (Seem) Hems near a Pb/Zn smelter in Guangdong, PR China. *Geoderma, 148*(3–4), 299–306.

Bhumi Publishing, India
November 2025

STATISTICAL ASSESSMENT OF GROUNDWATER QUALITY USING HYDRO-CHEMICAL PARAMETERS FOR DRINKING WATER IN DEOLA, SATANA, AND MALEGAON TEHSILS IN NASHIK, MAHARASHTRA

Chetan Ashokrao Patil[1], Pravin Mukund Nalawade*[1], Kailas Devaram Ahire[1], Bharat Laxman Gadakh[2], Nutan Vijay Khangar[3] and Ashish Vilas Mane[4]

[1]Department of Environmental Science,

[2]Department of Geography,

[3]Department of Statistics,

K.R.T. Arts, B.H. Commerce and A.M. Science (KTHM) College, Nashik, Maharashtra

[4]Department of Environmental Science, Fergusson College, Pune, Maharashtra

*Corresponding author E-mail: pmnalawade@gmail.com

Abstract:

Groundwater assessment is based on the hydrochemical parameters of the study area. The objective of this study is to determine the number of hydrochemical parameters to assess the groundwater quality of Nashik. Water samples were collected from the three tehsils in Nashik, namely Deola, Satana, and Malegaon, covering a total study area of approximately 3,819.441 square kilometres. From each tehsil, sixteen water samples were collected, comprising ten healthy samples and six borewell samples. All forty-eight samples were analyzed for hydrochemical parameters such as pH, temperature, electrical conductivity, solids in water, dissolved oxygen, turbidity, alkalinity ($CaCO_3$), carbonate and bicarbonate, chloride, sulphate (SO_4), fluoride (F), total hardness ($CaCO_3$), sodium, potassium, nitrate, nitrite, ammonia, orthophosphate, total phosphate, boron, aluminum, iron, manganese and silica concentrations and observations were recorded. The concentration levels of hydrochemical parameters indicated the quality of groundwater. The overall statistical assessment of groundwater revealed that all groundwater samples are suitable for drinking and irrigation, as the values of hydrochemical parameters do not exceed the permissible limits. However, the mean pH of the borehole water sample exceeds the allowable limit. Hence, by using the t-test, the comparison between the bore well and open well sample analysis revealed that at 95 % confidence, we can say that open healthy water is better for drinking and irrigation than bore well water

Keywords: Groundwater Quality, Water Quality Indicators, Assessment of Groundwater, Hydro-chemical Parameters.

1. Introduction:

Groundwater is a critical resource, particularly in semi-arid regions like Nashik, Maharashtra, where it supports agriculture, industry, and domestic needs. However, its behaviour is highly complicated due to varying geological formations, climatic conditions, and hydro-geochemical processes influenced by both natural and anthropogenic factors (Das, 2008; Khare & Varade, 2018). The quality of groundwater, determined by its physical, chemical, and biological characteristics, dictates its suitability for various uses. The intensified extraction and use of this resource often lead to its deterioration, with certain chemical constituents rendering it unfit for consumption or irrigation if they exceed safe limits (Purushtotham, 2011; Deshpande & Aher, 2011).

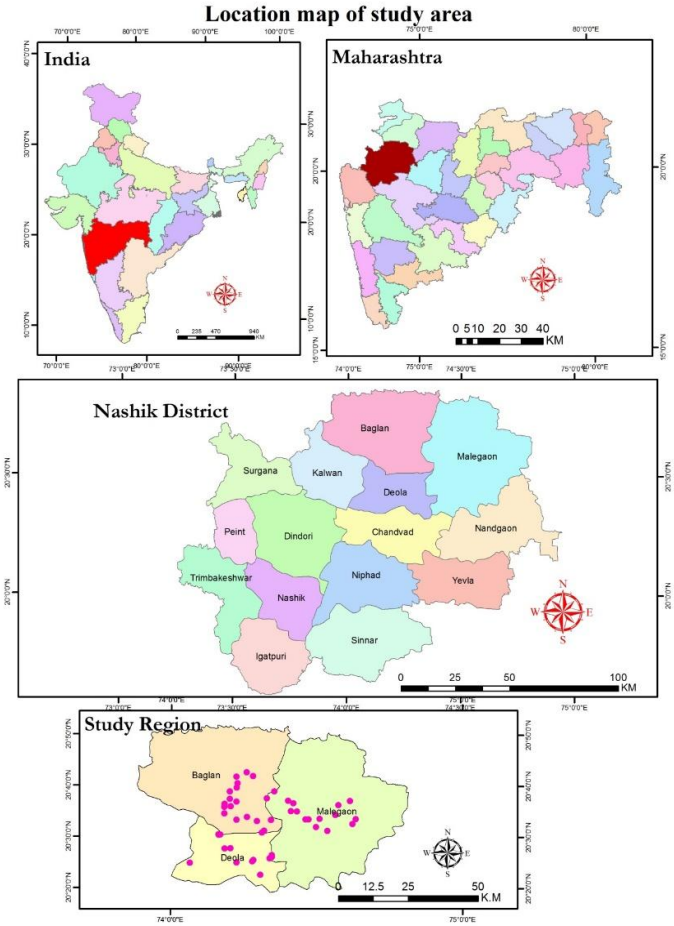
The geochemical signature of groundwater is shaped by mineral weathering, dissolution/precipitation reactions, ion exchange, and atmospheric deposition, further modified by human activities such as agriculture, sewage disposal, and industrial effluents (Jiang & Yan, 2010; Bozdag & Gocmez, 2013; Wagh, 2018). Globally, aquifers face increasing threats from pollutants like fluoride, arsenic, and nitrate (Subramani, 2005). In Maharashtra, the Groundwater Survey and Development Agency (GSDA) and the Central Ground Water Board (CGWB) have documented rising nitrate pollution, with many locations exceeding the safe limit of 45 mg/L, highlighting a pressing public health issue.

This study focuses on the hydrochemistry of groundwater in the Deola, Satana, and Malegaon tehsils of Nashik district. By employing a robust statistical assessment of a wide array of parameters, this research aims to provide a clear picture of groundwater suitability for drinking. A central question we address is whether the depth of water extraction shallow open wells versus deeper borewells significantly impacts water quality. The findings are intended to aid in the sustainable management of groundwater aquifers and agricultural planning in the region.

2. Study Area: Geography and Climate

Nashik district, the third largest in Maharashtra, is situated in the northern part of the state. The study area encompassing Deola, Satana, and Malegaon tehsils lies at the junction of the Girna and Mosam rivers, with an average elevation of 438 metres. The region forms part of the Deccan Plateau, characterized by a varied topography of lush mountain terrains and flat-topped hills.

The climate is classified as tropical and semi-arid. May is the hottest month, with average daily maximum temperatures reaching 40.6°C in Malegaon. The area receives an average annual rainfall of about 812 mm, predominantly during the southwest monsoon. Agriculture is the primary occupation, with crops like grapes, onions, and sugarcane dominating the landscape, which in turn influences groundwater quality through agricultural practices.



3. Hydrogeology

The Nashik district is predominantly underlain by the Deccan Trap basalts, a multi-layered sequence of volcanic lava flows from the Cretaceous to Eocene epochs. These basaltic flows, which cover about 85% of the area, are typically composed of a massive unit at the bottom and a vesicular unit at the top, separated by 'bole beds'.

Groundwater in this terrain occurs primarily in the upper weathered and fractured zones, extending to depths of 20-25 meters, forming unconfined aquifers. Deeper potential zones exist in the form of fractures and interflow zones, where groundwater can be semi-confined to confined. Shallow alluvial deposits along the Godavari, Mosam, and Girna rivers also form minor aquifers. This dual aquifer system is crucial for understanding the differing water qualities between open wells (tapping the shallow weathered zone) and borewells (tapping the deeper fractures).

4. Methodology for Analysis

4.1. Sample Collection and Analysis

Forty-eight groundwater samples (30 open wells, 18 borewells) were collected during the pre-monsoon season of 2020 from across the three tehsils. Samples were collected in pre-cleaned 2-litre polyethylene containers following standard protocols (APHA, 1992)

4.2 Analytical Methods

The samples were analyzed for 26 hydro-chemical parameters. The methods employed are standard for water quality analysis and are summarized in Table 1.

Table 1: Water quality parameters and their method of analysis

Category	Parameter	Method of Analysis
Physical	pH	pH Meter
	Temperature	Temperature Meter
	Electrical Conductivity (EC)	EC Meter
	Total Dissolved Solids (TDS)	Gravimetric (Oven Drying Method)
	Turbidity	Nephelometric Method
Chemical	Carbonate (CO_3^{2-})	Acid Titration (Strong Acid)
	Bicarbonate (HCO_3^-)	Acid Titration (Strong Acid)
	Dissolved Oxygen (DO)	Winkler's Iodometric Method
	Alkalinity as $CaCO_3$	Acid Titration Method
	Sulphate	Gravimetric Method
	Fluoride	Spectrophotometric Method
	Calcium	EDTA Titrimetric Method
	Total Hardness (as $CaCO_3$)	EDTA Titrimetric Method
	Sodium	Flame Photometric Method
	Potassium	Flame Photometric Method
	Nitrate	Brucine Colorimetric Method
	Nitrite	Spectrophotometric Determination
	Ammonia	Colorimetric Method
	Orthophosphate	Spectrophotometric Method
	Total Phosphate	Acid Digestion / Colorimetric Method
	Boron	ICP-AES (Inductively Coupled Plasma Atomic Emission Spectroscopy)
	Aluminium	Graphite Furnace AAS (Atomic Absorption Spectrometry)
	Iron	Spectrophotometric Determination
	Manganese	Spectrophotometric Method
	Silica	Molybdosilicate Method
	Chloride	Argentometric Titration (Silver Nitrate Method)

4.3. Statistical Analysis

The data were subjected to descriptive statistical analysis (mean, standard deviation, min, max). An independent samples t-test was used to compare the means of parameters between open well and borewell samples at a 95% confidence level ($p < 0.05$ indicating significance). Cluster analysis was also performed using SPSS to group samples with similar hydrochemical characteristics.

5. Results and Discussion:

5.1. Overall Groundwater Quality

The descriptive statistics for all 48 samples combined are presented in Table 2.

Table 2: Statistical Analysis of All Groundwater Samples (Open Wells & Borewells Combined)

Parameter	Min	Max	Std. Deviation	Mean	95% C.I. Lower	95% C.I. Upper
pH	7.10	8.70	0.47	7.77	7.64	7.91
Temperature (°C)	25.00	26.00	0.50	25.44	25.30	25.58
EC (µS/cm)	258.30	780.20	184.18	504.23	452.67	555.79
TDS (mg/L)	102.03	1410.05	253.62	620.87	547.20	694.50
CO_3^{2-} (mg/L)	100.03	191.28	29.22	132.17	123.99	140.35
HCO_3^- (mg/L)	201.12	490.89	76.95	306.98	285.44	328.53
DO (mg/L)	2.80	6.10	0.89	4.26	4.00	4.52
Turbidity (NTU)	2.00	4.00	0.48	2.76	2.63	2.90
Alkalinity as $CaCO_3$ (mg/L)	202.12	398.25	56.99	299.78	283.83	315.74
Sulphate (mg/L)	196.23	311.00	36.91	234.40	223.68	245.12
Fluoride (mg/L)	0.21	1.00	0.18	0.45	0.40	0.50
Calcium (mg/L)	96.00	188.00	20.97	126.85	120.76	132.94
Total Hardness as $CaCO_3$ (mg/L)	208.10	525.00	80.97	306.37	283.71	329.04
Sodium (mg/L)	90.25	188.45	21.19	121.79	115.85	127.72
Potassium (mg/L)	0.24	0.90	0.14	0.49	0.46	0.53
Nitrate (mg/L)	10.45	51.98	11.90	26.01	22.68	29.34
Nitrite (mg/L)	0.51	2.12	0.34	1.04	0.95	1.14
Ammonia (mg/L)	0.63	1.99	0.26	1.01	0.94	1.08
Orthophosphate (mg/L)	0.05	0.14	0.02	0.09	0.09	0.10
Total Phosphate (mg/L)	0.02	0.09	0.01	0.04	0.04	0.05

Boron (mg/L)	2.00	4.98	0.63	2.74	2.56	2.91
Aluminium (mg/L)	0.09	0.17	0.02	0.11	0.10	0.11
Iron (mg/L)	0.30	0.63	0.09	0.42	0.39	0.45
Manganese (mg/L)	0.10	0.27	0.04	0.17	0.16	0.18
Silica (mg/L)	21.03	55.18	8.87	98.93	36.44	41.41
Chloride (mg/L)	196.12	288.65	21.58	232.58	120.98	132.72

The results indicate that the mean values for most parameters, including key indicators like Nitrate, Fluoride, and TDS, fall within the permissible limits set by the WHO and BIS (IS 10500:2012). This general suitability can be attributed to two primary factors: the prevalence of organic farming in the area, which minimizes the leaching of inorganic fertilizers and pesticides, and the high rainfall in 2019-20, which likely diluted contaminant concentrations. This is a positive shift from the high EC levels (>2000 µmhos/cm) reported in some parts of Satana during the drought conditions of 2011.

5.2. Open Well vs. Borewell: A Statistical Comparison

The t-test analysis (Table 3) revealed a statistically significant difference between open wells and borewells for several parameters. Most critically, the mean pH of borewell water (8.27) was significantly higher than that of open wells (7.47), pushing beyond the desirable limit of 8.5.

Table 3: Statistical comparison between Well and Borewell samples (Selected Parameters)

Sr. No.	Parameter	Well Mean	Borewell Mean	t-statistic	p-value	Significance
1	pH	7.47	8.27	-10.22	0.00*	Significant
2	Temperature	25.46	25.38	0.52	0.61	NS
3	Electrical Conductivity	394.20	687.61	-8.44	0.00*	Significant
4	TDS	555.77	729.37	-2.41	0.02*	Significant
5	CO_3^{2-}	117.65	156.36	-5.77	0.00*	Significant
6	HCO_3^-	263.23	379.91	-7.50	0.00*	Significant
7	DO	4.71	3.51	5.88	0.00*	Significant
8	Turbidity	2.79	2.70	0.63	0.53	NS
9	Alkalinity (as $CaCO_3$)	263.15	360.82	-10.43	0.00*	Significant
10	Sulphate	238.48	227.59	0.99	0.33	NS
11	Fluoride	0.41	0.52	-2.28	0.03*	Significant
12	Calcium	122.79	133.61	-1.77	0.08	NS (p>0.05)
13	Total Hardness (as $CaCO_3$)	298.97	318.69	-0.81	0.42	NS

14	Sodium	110.76	140.17	-6.27	0.00*	Significant
15	Potassium	0.46	0.54	-1.99	0.05	Borderline
16	Nitrate	24.77	28.08	-0.93	0.36	NS
17	Nitrite	1.06	1.02	0.36	0.72	NS
18	Ammonia	0.93	1.14	-3.04	0.00*	Significant
19	Orthophosphate	0.09	0.09	-0.07	0.94	NS
20	Total Phosphate	0.04	0.04	0.92	0.36	NS
21	Boron	2.74	2.73	0.05	0.96	NS
22	Aluminium	0.10	0.12	-3.86	0.00*	Significant
23	Iron	0.40	0.46	-2.32	0.02*	Significant
24	Manganese	0.15	0.20	-5.02	0.00*	Significant
25	Silica	39.92	37.28	0.99	0.32	NS
26	Chloride	240.21	220.87	3.31	0.00*	Significant

***Statistically significant ($p < 0.05$)**

Borewells showed significantly higher levels of EC, TDS, carbonate, bicarbonate, alkalinity, fluoride, sodium, ammonia, iron, and manganese. This can be explained by the longer residence time and intense water-rock interactions in deeper aquifers. The alkaline conditions (high pH) favour the dissolution of fluoride from minerals like fluorite and biotite. Conversely, open wells showed higher levels of Dissolved Oxygen (DO) and Nitrate, reflecting their connectivity to the surface and greater vulnerability to surface contamination, though the nitrate levels remained within safe limits.

5.3. Cluster Analysis

The cluster analysis grouped the 48 samples into six distinct clusters based on their hydrochemical similarity (Table 4). The key insight from this analysis is that all parameters across all clusters remain within permissible limits. This means that the groundwater quality in the study area, while variable, is consistently acceptable. This clustering provides a baseline; should any parameter deteriorate in the future, this analysis will help pinpoint specific geographic clusters or well types that are most affected, allowing for targeted intervention.

Table 4: Cluster analysis for well and borewell samples

Parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Grand Centered
pH	7.50	7.48	7.52	8.18	7.47	8.13	7.77
Temperature	25.50	25.17	25.67	25.35	25.40	26.00	25.44

EC (µS/cm)	430.97	314.51	374.10	700.95	364.44	645.41	504.23
TDS (mg/L)	247.20	455.44	77.13	660.43	587.46	1287.71	620.87
CO_3^{2-} (mg/L)	116.85	124.45	114.90	125.95	112.32	161.17	132.17
HCO_3^- (mg/L)	287.77	251.65	247.69	368.06	259.87	385.66	306.98
DO (mg/L)	4.38	5.00	4.85	3.59	4.73	3.67	4.26
Turbidity (NTU)	2.90	2.72	2.90	2.74	2.66	2.80	2.76
Alkalinity (mg/L)	274.44	250.32	262.84	349.79	274.89	322.89	299.78
Chloride (mg/L)	231.28	246.21	253.16	225.25	234.64	207.43	232.96
Sulphate (mg/L)	220.87	246.09	245.05	238.01	232.06	204.16	234.40
Fluoride (mg/L)	0.38	0.42	0.42	0.47	0.40	0.71	0.45
Total Hardness (mg/L)	305.97	351.90	317.80	302.51	247.90	410.03	306.37
Sodium (mg/L)	112.86	107.61	112.50	135.83	109.65	147.42	121.79
Potassium (mg/L)	0.49	0.51	0.42	0.50	0.46	0.70	0.49
Nitrate (mg/L)	25.00	24.57	23.02	30.72	20.33	29.23	29.01*
Nitrite (mg/L)	1.10	1.14	0.98	1.03	0.93	1.32	1.04
Ammonia (mg/L)	0.85	0.93	0.90	1.04	0.97	1.65	1.01
Orthophosphate (mg/L)	0.09	0.09	0.09	0.09	0.09	0.10	0.09
Total Phosphate (mg/L)	0.04	0.05	0.04	0.04	0.05	0.03	0.04
Boron (mg/L)	2.65	2.50	2.81	2.54	2.81	4.08	2.74
Aluminium (mg/L)	0.10	0.10	0.10	0.11	0.10	0.14	0.11
Iron (mg/L)	0.35	0.43	0.40	0.43	0.42	0.50	0.42
Manganese (mg/L)	0.17	0.15	0.15	0.19	0.15	0.22	0.17
Silica (mg/L)	39.87	38.35	38.37	37.80	39.39	44.16	38.93
Calcium (mg/L)	131.55	121.35	124.95	124.60	122.34	160.08	126.85

Conclusion:

This comprehensive statistical assessment leads to several key conclusions: The groundwater in the Deola, Satana, and Malegaon tehsils is generally of good quality and suitable for drinking and irrigation, with most hydro-chemical parameters within permissible limits. This is a positive outcome, likely supported by organic farming practices and adequate rainfall. The most significant finding is the clear qualitative difference between water sources. Borewell water is more mineralized, alkaline, and has higher concentrations of elements like fluoride and sodium compared to open well water. Critically, the mean pH of borewell water was found to be

significantly higher than the desirable limit. Statistical testing (t-test) confirms that at a 95% confidence level, open well water is a better source for drinking and irrigation than borewell water in this region. The cluster analysis confirms that while there is natural hydrochemical variation across the area, no cluster currently shows signs of severe contamination. This study demonstrates that a statistical approach to water quality data is not just an academic exercise but a vital tool for making informed, evidence-based decisions for water resource management and public health.

References:

1. Adagunodo, A., Sunmonu, L. A., Ojoawo, A., Oladejo, O. P., & Olafisoye, E. R. (2013). The hydrogeophysical investigation of Oyo State Industrial Estate Ogbomosho, Southwestern Nigeria using vertical electrical soundings. Research Journal of Applied Sciences, Engineering and Technology, 5, 1816–1829. https://doi.org/10.19026/rjaset.5.4944
2. Adagunodo, T. A., Hammed, O. S., Usikalu, M. R., Ayara, W. A., & Ravisankar, R. (2018a). Radioactivity and radiological hazards from a kaolin mining field in Ifonyintedo, Nigeria. MethodsX, 5, 362–374. https://doi.org/10.1016/j.mex.2018.04.009
3. Adagunodo, T. A., Lüning, S., Adeleke, A. M., Omidiora, J. O., Aizebeokhai, A. P., Oyeyemi, K. D., *et al.,* (2018c). Evaluation of $0 \leq M \leq 8$ earthquake data sets in African–Asian region during 1966–2015. Data in Brief, 17, 588–603. https://doi.org/10.1016/j.dib.2018.01.049
4. Adagunodo, T. A., Sunmonu, L. A., Oladejo, O. P. (2014). Effect of constructing high-rise buildings without a geophysical survey. Nigerian Journal of Physics Special Edition, 91–100.
5. Adelusi, A. O., Ayuk, M. A., & Kayode, J. S. (2014). VLF-EM and VES: An application to groundwater exploration in a Precambrian basement terrain SW Nigeria. Annals of Geophysics, 57(1), 1–11.
6. Ademeso, O. A. (2009). Deformation traits in the charnockitic rocks of Akure area, Southwestern Nigeria. Asian Journal of Earth Sciences, 2, 113–120. https://doi.org/10.3923/ajes.2009.113.120
7. Adepelumi, A. A., Yi, M. J., Kim, J. H., Ako, B. D., & Son, J. S. (2006). Integration of surface geophysical methods for fracture detection in crystalline bedrock of Southwestern Nigeria. Hydrogeology Journal, 14, 1284–2130.
8. Adeyemo, I., Omosuyi, G., Ojo, B. T., & Abiola, A. (2017). Groundwater potential evaluation in a typical basement complex environment using GRT index: A case study of

Ipinsa-Okeodu area, near Akure Nigeria. Journal of Geoscience and Environmental Protection, 5, 240–251.

9. Adiat, K. N., Nawawi, M. N. M., & Abdullah, K. (2012). Assessing the accuracy of GIS-based elementary multicriteria decision analysis as a spatial prediction tool: A case of predicting potential zones of sustainable groundwater resources. Journal of Hydrology, 440, 75–89. https://doi.org/10.1016/j.jhydrol.2012.03.028
10. Adiat, K. N., Nawawi, M. N. M., & Abdullah, K. (2013). Application of multicriteria decision analysis to geo-electric and geologic parameters for spatial prediction of groundwater resources potential and aquifer evaluation. Pure and Applied Geophysics, 170, 453–471. https://doi.org/10.1007/s00024-012-0501-9
11. Adiat, K. N., Olayanju, G. M., Omosuyi, G. O., & Ako, B. D. (2009). Electromagnetic profiling and electrical resistivity soundings in groundwater investigation of a typical basement complex: A case study of Oda town, Southwestern Nigeria. Ozean Journal of Applied Sciences, 2(4), 333–359.
12. Aghazadeh, N., & Mogaddam, A. A. (2010). Assessment of groundwater quality and its suitability for drinking and agricultural uses in the Oshnavieh area Northwest of Iran. Journal of Environmental Protection, 1, 30.
13. Aher, K. R., Patil, S. M., & Mane, V. P. (2015). Preliminary study in irrigational quality of groundwater sources in parts of Soygaon block, District Aurangabad, India. International Research Journal of Earth Sciences, 3(2), 7–12.
14. Alagbe, O. A., Sanusi, S. O., & Bamigboye, A. A. (2019). 2D electrical resistivity prospecting for groundwater at the premises of the staff quarters of Elizade University, Ilara-Mokin, Ondo State, Nigeria. World Journal of Innovative Research, 6(2), 100–108.
15. Anbazhagan, S., & Das, M. G. (2014). Hydrogeochemical studies in hard rock aquifer system, Hosur, India. Indian Journal of Geochemistry, 22(2), 519–535.
16. Andrade, E. M., Palacio, H. A. Q., Souza, I. H., Leao, R. A. O., & Guerreiro, M. J. (2008). Land use effects in groundwater composition of an alluvial aquifer (Trussu River, Brazil) by multivariate techniques. Environmental Research, 106, 170–177.
17. APHA. (1992). Standard methods for the examination of water and wastewater (18th ed.). American Public Health Association.
18. Avvannavar, S. M., & Shrihari, S. (2008). Evaluation of water quality index for drinking purposes for river Netravathi, Mangalore, South India. Environmental Monitoring and Assessment, 143, 279–290.
19. Ayers, R. S., & Westcot, D. W. (1985). Water quality for agriculture (pp. 29–70). FAO.

20. Azaza, F. H., Ketata, M., Bouhlila, R., Gueddari, M., & Ribiero, L. (2011). Hydrogeochemical characteristics and assessment of drinking water quality in Zeuss-Koutine aquifer, southeastern Tunisia. Environmental Monitoring and Assessment, 174, 283–298.
21. Bahar, M. M., & Yamamuro, M. (2008). Assessing the influence of watershed land use patterns on major ion chemistry of river waters in the Shimousa upland, Japan. Chemistry and Ecology, 24(5), 341–355.
22. Bahar, M., & Reza, S. (2010). Hydrochemical characteristics and quality assessment of shallow groundwater in a coastal area of southwest Bangladesh. Environmental Earth Sciences, 61, 1065–1073.
23. Bhardwaj, V., & Singh, D. S. (2010). Surface and groundwater quality characterization of Deoria District, Ganga Plain. Environmental Earth Sciences. https://doi.org/10.1007/s12665-010-0709-x
24. Bozcu, M., Yag˘murlu, F., & S¸entürk, M. (2007). Some neotectonics and paleoseismological properties of Fethiye-Burdur fault zone, SW-Turkey. Geological Engineering Journal, 31(1), 25–48.
25. Bundela, P. S., Sharma, A., Pandey, A. K., Pandey, P., & Awasthi, A. K. (2012). Physicochemical analysis of groundwater near municipal solid waste dumping sites in Jabalpur. IJPAES, 2, 217–222.
26. Capan, U. (1980). Approaches petrology, petrochemical characteristics and internal structure of the Taurus Belt ophiolite massifs (Doctoral dissertation). Hacettepe University Institute of Science.
27. Chowdhury, A. (2006). Evaluation of groundwater potential in West Medinipur district using remote sensing and GIS (Doctoral dissertation, IIT Kharagpur).
28. Chowdhury, A., Jha, M. K., Chowdary, V. M., & Mal, B. C. (2009). Integrated remote sensing and GIS based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. International Journal of Remote Sensing, 30(1), 231–250.
29. Craig, E., & Anderson, M. P. (1979). The effects of urbanization on groundwater quality: A case study of groundwater ecosystems. Environmental Conservation, 30(2), 104–130.
30. Datta, A., Gaikwad, H., Kadam, A., & Umrikar, B. N. (2020). Evaluation of groundwater prolific zones in unconfined basaltic aquifers of Western India using geospatial modeling and MIF technique. Modeling Earth Systems and Environment. https://doi.org/10.1007/s40808-020-00791-0

31. Datta, P. S., & Tyagi, S. K. (1996). Major ion chemistry of groundwater in Delhi area: Chemical weathering processes and groundwater flow regime. Geological Society of India, 47(2), 179–188.
32. Deshpande, S. M., & Aher, K. R. (2011). Hydrogeochemistry and quality assessment of groundwater in Chikalthana industrial area of Aurangabad, Maharashtra, India. Bionano Frontier, 4(1), 157–16.
33. Doneen, L. D. (1964). Notes on water quality in agriculture. Department of Water Science and Engineering, University of California, Davis.
34. Eaton, F. M. (1950). Significance of carbonates in irrigation waters. Soil Science, 69(2), 123–134. https://doi.org/10.1097/00010694-195002000-00004
35. Gowd, S. S. (2005). Assessment of groundwater quality for drinking and irrigation purposes: A case study of Peddavanka watershed, Anantapur District, Andhra Pradesh, India. Environmental Geology, 48(6), 702–712. https://doi.org/10.1007/s00254-005-0009-z
36. Handa, B. K. (1969). Description and classification of media for hydrogeochemical investigations. In Symposium on Groundwater Studies in Arid and Semiarid Regions.
37. Indian Council of Medical Research (ICMR). (1975). Manual of standards of quality for drinking water supplies (Special Report Series No. 44).
38. Rao, Y. S., & Jugran, D. K. (2003). Delineation of groundwater potential zones and zones of groundwater quality suitable for domestic purposes using remote sensing and GIS. Hydrological Sciences Journal, 48(5), 821–833.
39. Reynolds, J. M. (1997). An introduction to applied and environmental geophysics. Wiley.
40. Sakthivadivel, R., & Nagar, R. K. (2003). Private initiative for groundwater recharge—Case of Dudhada Village in Saurashtra. IWMI-Tata Discussion Paper 15.
41. Saraf, A. K., & Choudhury, P. R. (1998). Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. International Journal of Remote Sensing, 19, 1825–1841.

Bhumi Publishing, India
November 2025

ROLE OF FUNGI IN BIOREMEDIATION OF TEXTILE DYES

Pravin V. Gadakh

Department of Microbiology,

Arts, Science and Commerce College, Badnapur, Dist. Jalna (M.S.) 431202

Corresponding author E-mail: pvgadakh@gmail.com

Abstract:

Fungal bioremediation offers an efficient and eco-friendly approach for removing toxic dyes and industrial pollutants. In this study, soil fungi such as *Aspergillus niger* and *Phanerochaete chrysosporium* exhibited high decolorization efficiency—up to 90% within six days—through extracellular ligninolytic enzymes including laccase and lignin peroxidase, along with biosorption by fungal mycelia. The fungi effectively degraded dyes such as Nigrosin, Basic fuchsin, and Malachite green, showing performance comparable to well-known white-rot fungi. These findings highlight the strong potential of fungi as cost-effective agents for biodegradation and wastewater treatment.

Keywords: Biodegradation, Myco-Remediation, Accumulation, Dyes, Effluents, Fungi.

Introduction:

Bioremediation is an effective process used to degrade heavy metals, toxicants, and synthetic chemical compounds under suitable environmental conditions. The degradation of textile dyes by bacteria, yeast, and filamentous fungi has been reported by Khan *et al.* (2013). Among these microorganisms, fungi are considered more affordable and efficient for dye degradation because they produce extracellular enzymes capable of breaking down complex dye molecules and other chemical pollutants present in wastewater (Raheem & Shearer, 2002). The tube agar method provides a simple and rapid approach for screening fungal isolates for their dye-degrading ability, making it useful for selecting efficient strains for further studies (Lopez *et al.,* 2006).

A fungal species Aspergillus niger and *P. chrysosporium* capable of waste water treatment and dye decolorization. In liquid medium, Nigrosin, Basic Fuchsin, and Malachite Green dyes were decolorized within 6 days by up to 90%. Kanmani *et al.* (2011) reported that Nigrosin was a substrate for the ligninolytic enzyme lignin peroxidase. Enzyme systems produced by fungi for the decolourization of azo dyes, moreover, dye molecules display a high structural variety, and they are degraded by only few enzymes. These enzymes have one common mechanistic feature; they are all redox-active molecules and thus, exhibit relatively wide substrate specificities (Mester and Tien, 2000). In case of enzymatic remediation of azo dyes, azo reductases and laccases seem to be the most promising enzymes. These enzymes are multicopper phenol

oxidases that decolourize azo dyes through a highly nonspecific free radical mechanism forming phenolic compounds, thereby avoiding the formation of toxic aromatic amines (Wong and Yu, 1999). Ezeronye and Okerentugba, (1999) reported that the fungi create system for treatment of azo dye and produced enzymes like peroxidase and phenol oxidase in the treatment of azo dye degradation. Camarero *et al.* (2005) reported the oxidation of a carbonium ion in a nucleophilic attack by water on the phenolic ring carbon bearing the azo linkage to produce 3-diazenyl-benzenesulfonic acid (III) and 1, 2-naphthoquinone then takes place.

Use of *A. niger* and *P. crysosporium* as dye biodegrader or decolourizer has been studied in this report and capable of decolourization may be attributed to either through the action of extracellular enzymes activities such as laccase and/or biosorption by the fungal biomass. Laccase production by the soil fungal species have been studied, this test was performed to know, whether laccase enzyme plays any role in biodegradation of dyes. Furthermore, the soil fungal strains also showed promising decolorization activities against tested dyes. Ali *et al.* (2009) and Vasudev (2011) reported that Malachite green was readily degraded in liquid culture by *A. flavus*, *A. solani* and some white rot fungi within six days up to 96%, as also shown in his study. Results of the dye biodegradation by soil fungi in this study using spectrophotometric analysis were even comparable with the percent dye decolorization exhibited by the white-rot fungus *Trametes versicolor* and *Pleurotus ostreatus* (Yao *et al.,* 2009), and even *P. chrysosporium* (Bumpus and Brock, 1988).

Fungi in soil possess ligninolytic enzymes and play an important role in the degradation of lignocellulose in soil ecosystems (Okino *et al.,* 2000). These lignin-degrading enzymes are directly involved not only in the degradation of lignin in their natural lignocellulosic substrates but also in the degradation of various xenobiotic compounds, including dyes. Moreover, ligninolytic enzymes have been reported to oxidize many recalcitrant substances such as chlorophenols, polycyclic aromatic hydrocarbons (PAHs), organophosphorus compounds, and phenols (Wesenberg *et al.,* 2003).

Additionally, it is not unusual for some species to demonstrate both enzyme-mediated degradation and biosorption in the decolorization of textile dyes (Park *et al.,* 2007; Shahid *et al.,* 2013). It is thus feasible that in addition to the production of extracellular enzymes, the ability of the dye effluent soil fungi to decolorize synthetic dyes is coupled also with their biosorption abilities (Kaushik and Malik, 2009). We have also observed dye absorption by the test fungal mycelium under light microscope (1500 x). This may account for the more efficient textile dye biodegradation by the soil fungal strains (Kirby *et al.,* 2000). It is therefore, possible that the ability of dye effluent soil-derived fungi to degrade malachite green, nigrosin and basic fuchsin as revealed in this study can be largely attributed to the lignin-degrading enzyme system of the

organism. In addition to extracellular enzymes, it is also likely that dye decolorization activity of these fungi could also be attributed to the ability of their mycelia to adsorb/absorb the dye. Bioremediation rate of dyes was higher with individual dyes as compared to dye mixture, which could be due the reason that a mixture of dyes forms different complex structures which become resistant for biodegradation.

Decolorization of dyes was studied under stationary and shaking conditions by Rani *et al.* (2014). encouraging results were obtained after 3 days, but maximum decolorization of all the dyes were obtained after 6 days. In this study, they observed higher decolorization under shaking conditions by *P. chrysosporium* and *A. niger*, which could be due to better oxygenation of the fungus and regular contact of secreted enzymes with dye molecules to decolorize it, moreover agitation also helps the fungus to grow better. Disappearance of dye color may be due to biodegradation of chromophore in dye molecule because of extracelluar enzyme production by fungi along with absorption and adsorption. Due to the environmentally friendly techniques, it utilizes, bioremediation has been characterized as a soft technology. Its cost-effectiveness and the little disturbance in the environment render this technology a very attractive and alternative method of choice. The identification and research of new fungal strains with the aid of molecular techniques will further improve practical applications of fungi and it is anticipated that fungal remediation will be soon a reliable and competitive dye remediation technology. Numerous microorganisms such as algae, yeast, bacteria and fungi possess the ability to mineralize and decolorize various dyes (Varjani and Upasani, 2019; Pratiwi *et al.,* 2019). It is a method in which waste and toxic chemicals are converted into non-harmful or less toxic compounds by plants and/or microorganisms (Sharma, 2021).

Being an economical, eco-friendly and less sludge-producing process, fungal treatment is a very advantageous process used by researchers to find new ways for bioremediation. Contrary to bacteria, fungi robustly degrade multifaceted organic complexes through the production of extracellular ligninolytic enzymes, including manganese peroxidase,

Currently more focus is given on using fungi for bioremediation. Bioremediation is an effective, economical and appropriate treatment approach for polluting materials (Maljaei *et al.,* 2009). The method of using fungi in bioremediation is termed as fungal bioremediation or mycoremediation. Fungi have been used for the biotransformation of industrial waste products such as dyes and for eliminating toxins from the ecosystem (Balabanova *et al.,* 2018). They also have the ability to survive and propagate in extreme environmental conditions. Fungi metabolize and immobilize by enzyme produced activity the dyes, either by storing them in different parts of the cell or by translocating them through fungal hyphae and eventually degrading them. Table 1 presents the list of fungi capable of degrading dyes. These features allow fungi as potential

candidates to remove dyes from the environment and make them usable for bioremediation in cost-effective and environmental-friendly ways (Zahran *et al.,* 2019). This article focuses on fungi as a promising alternative to dye degradation. Nigam *et al.,* (2000), reported that the *T. versicolor* the ability to degrade a variety of pharmaceuticals. Diclofenac, naproxen, indomethacin, ibuprofen, and fenoprofen, while ketoprofen, clofibric acid, propyphenazone, and gemfibrozil were only partially degraded. Lac enzyme was shown to preferentially remove diclofenac, naproxen, indomethacin, and this indicated that intracellular enzymes may be involved in the degradation of other compounds. *T. versicolor* removed >99.9% and ~40% of diclofenac and ketoprofen, respectively, within 14 days (Deska *et al.,* 2019).

Mechanism of Dye Degradation:

Biodegradation has at least three steps; a minor change in an organic molecule leaving the main structure still intact, fragmentation of a complex organic molecule in such a way that the fragments could be reassembled to yield the original structure, and complete mineralization i.e., transformation of organic molecules to mineral forms, including carbon dioxide or methane, plus inorganic forms of other elements that might have contained the original structures (Singh *et al.,* 2010).

Biological Methods for Dye Decolorization and Degradation:

Aerobic and anaerobic methods involve the use of microbes for the degradation of organic dyes. Microbes or separated enzymes can perform the decolorization of dyes. Microbial fuel cells are devices that convert chemical energy to electrical energy with the help of microorganisms. Specific bacteria having the ability to extract electrons are attached to the anode and carry out the oxidation of the organic matter, releasing protons and carbon dioxide as the end products in the anode chamber. The reduction of oxygen takes place in the cathode chamber, where the electrons generated in the anode chamber are carried by an electrical circuit. This way, microorganisms achieve oxidation of organic matter (such as dyes) and convert the energy into electricity. In the last few years, biologically originated nanoparticles are also been used for the photocatalytic degradation of dyes (Joshi *et al.,* 2018 and Aravind *et al.,* 2021).

Recent Advancements in Biodecolorization and Biodegradation of Dyes:

Dyes are complex synthetic compounds manufactured artificially and are highly persistent in natural environments, as these chemicals were intended to be chemically and photolytically stable (Nigam *et al.,* 2002 and Rieger *et al.,* 2002). Their release into the environment is potentially hazardous, as it involves ecotoxicity risk and can affect the food chain. Water-soluble dyes like acid, reactive, disperse, and basic dyes have less bioaccumulation (Van der, 2002). It is reported that ionic dyes have the least bioaccumulation potential (but some acid dyes may bioaccumulate), whereas non-ionic dyes and pigments, however, have a high bioaccumulation

potential (Anliker *et al.,* 1988). Unlike physicochemical methods of dye decolorization, biological methods are relatively economical, more efficient, environment-friendly, and more versatile (Ali, 2009). Using biological agents such as microorganisms has considerable advantages over traditional methods. The processes are relatively inexpensive and have lower running costs. Moreover, this method also offers complete mineralization of the organic pollutants.

Table 1: Reports on the use of fungal cultures for dye degradation

Fungi	Dye	Decolorization (%)	References
Coriolopsis sp.	Crystal Violet	85.1	Munck *et al.* (2018)
	Cotton Blue	79.6	
Peyronellaea prosopidis	Scarlet RR	90	Bankole *et al.* (2018)
Aspergillus flavus SA2	Acid Red 151 and Orange II	67	Ali *et al.* (2018)
Aspergillus bombycis	Reactive Red 31	99.02	Khan *et al.* (2013)
Aspergillus niger	Malachite Green	82.6	Alam *et al.* (2018)
Ceriporiala cerata	Congo Red	90	Wang *et al.* (2017)
Scheffersomyces spartinae	Acid Scarlet 3R	> 90 dec	Tan *et al.* (2016)
Phanerochaete chrysosporium	Mixture of Malachite Green, Nigrosin and Basic Fuchsin	78.4	Rani *et al.* (2014)
Myceliophthora vellerea	Reactive Blue 220	80	Patel *et al.* (2013)
Mixed fungal cultures of*Pleurotus ostreatus* (BWPH), *Gloeophyll um odoratum* (DCa), and *Fusarium oxysporum* (G1)	Brilliant Green and Evans Blue	74.3	Przystas *et al.* (2013)
Aspergillus sp.	Methyl Violet	95	Kumar *et al.* (2012)
Pleurotus ostreatus	Acid Red 27	85	Ali and El-Mohamedy (2012)

Factors Affecting Dye Biodegradation:

Biological treatment systems are highly variable, and in textile effluents, there are several factors that can affect the biodegradation of the azo dyes. Temperature effect on the growth of fungi and also fungi produce enzymes at specific temperature. pH, also have great important for the growth of fungi almost fungi grow in between the 5.5- 6.5 pH, and also aeration needed to spreads fungi on substrates for consumption, of substrates to consume air from environment or artificially provides condition and the type of reducing agents used, microbial consortium, etc., are the factors that can affect the biodegradation of dyes. Further, the type of dye, the functional groups of the dye, its concentration, additives such as mordants, and their concentration in the effluent are also important while considering the wastewater treatment strategy. Azo dyes are not readily degraded in aerobic conditions, although the specialized enzymatic machinery for aerobic degradation of certain azo dyes has been reported (Stolz, 2001). In anaerobic systems, azo dyes are degraded using non-specific azo reductase enzymes and are converted into aromatic amines that may or may not be degraded in anaerobic systems. Subsequent aerobic biodegradation of the aromatic amines is necessary, as the accumulation of these amines can prove lethal to the biological system of the treatment plant. Studies show that several bacteria are capable of dye decolorization. The enzymes involved are mostly azo and nitro reductases that depend on one or the other co-factors, such as NAD or FAD, for their catalytic activity (Rafii *et al.,* 1993). The factors affecting the decolorization and biodegradation of dye compounds through fungal bioremediation, such as pH, temperature, dye concentration, agitation, effects of carbon and nitrogen sources, dye structure, enzymes, electron donor and redox mediators are discussed in this report. The report also includes a summary on the mechanism and kinetics of dye degradation as well as recent advances and future perspectives in mycoremediation of dyes.

Conclusion:

Indigenous microorganism has the ability to remediate the dye from the textile effluent. Therefore, as a preliminary step in the development of textile waste effluents treatment process use indigenous fungal species, in general, microbes (bacteria, fungi, and algae) and plants could be used, or their enzymes are widely applicable for dye adsorption, catalysis, decolorization and degradation applications. Also, the success of a microbial process for colour removal from the effluent depends on the utilization of microorganisms that effectively decolourize synthetic dyes of different chemical structures. The fungal degradation/decolourization of textile dyes has been demonstrated mainly in the laboratory studies.

Future Perspectives:

Based on the investigations of review on biodegradation of dyes by using fungi literature, it is clear that within the microbial diversity, fungi are much important for bio-degradation process of hazardous dyes and effluents. Further, investigations on mycoremediation have also been shown an inhibition in decolourizing fungal strain compared to their growth in a normal medium that might be a reason to get a lower percentage of dye degradation/decolourization after using of potential fungal strains for the same. Inhibition in fungal growth during the dye degradation/decolourization against some specific dye compounds clearly indicates the inefficiency of used fungal strain, might be due to toxicity of dye that suppresses the production of enzymes as well as mycelial growth. Proper degradation/decolourization of coloured wastewater from textile industries is major environmental concern. Amongst different chemical, physical and biological treatment methods, the biotechnological approaches based on fungi, are the most effective and environmentally friendly methods. Optimization of the culture media in carbon sources or nutrients and mediators' molecules is very important to obtain a good output of pollutants degradations.

References:

1. Abdel-Raheem, A., & Shearer, C. A. (2002). Extracellular enzyme production by freshwater ascomycetes. Fungal Diversity, 11, 1–19.
2. Alam, M. Z., Khan, M. J. H., Kabbashi, N. A., & Sayem, S. M. A. (2018). Development of an effective biosorbent by fungal immobilization technique for removal of dyes. Waste and Biomass Valorization, 9, 681–690.
3. Ali, H., Ahmed, W., & Haq, T. (2009). Decolorization and degradation of malachite green by Aspergillus flavus and Alternaria solani. African Journal of Biotechnology, 8(8), 1574–1576.
4. Ali, N. F., & El-Mohamedy, R. S. R. (2018). Microbial decolorization of textile wastewater. Journal of Saudi Chemical Society, 16(2), 117–123.
5. Anliker, R., Moser, P., & Poppinger, D. (1988). Bioaccumulation of dyestuffs and organic pigments in fish: Relationships to hydrophobicity and steric factors. Chemosphere, 17(8), 1631-1644.
6. Aravind, M., Ahmad, A., Ahmad, I., *et al.,* (2020). Critical green routing synthesis of silver NPs using jasmine flower extract for biological activities and photocatalytical degradation of methylene blue. Journal of Environmental Chemical Engineering, Article 1048-77.

7. Balabanova, L., Slepchenko, L., Son, O., & Tekutyeva, L. (2018). Biotechnology potential of marine fungi degrading plant and algae polymeric substrates. Frontiers in Microbiology, 9, 15-27.
8. Bankole, P. O., Adekunle, A. A., Obidi, O. F., Chandanshive, V. V., & Govindwar, S. P. (2018). Biodegradation and detoxification of Scarlet RR dye by a newly isolated filamentous fungus, Peyronellaea prosopidis. Sustainable Environment Research, 28(5), 214–222.
9. Bumpus, J. A., & Brock, B. J. (1988). Biodegradation of crystal violet by the white rot fungus Phanerochaete chrysosporium. Applied and Environmental Microbiology, 54(5), 1143–1150.
10. Camarero, S., Ibarra, D., Martínez, M. J., & Toca-Herrera, J. L. (2005). Lignin-derived compounds as efficient laccase mediators for decolourization of different types of recalcitrant dyes. Applied and Environmental Microbiology, 71(4), 1775–1784.
11. Deska, M., & Kończak, B. (2019). Immobilized fungal laccase as "Green catalyst" for the decolourization process – state of the art. Process Biochemistry, 84, 112–123.
12. Ezeronye, O. U., & Okerentugba, P. O. (1999). Performance and efficiency of a yeast biofilter for the treatment of a Nigerian fertilizer plant effluent. World Journal of Microbiology and Biotechnology, 15, 515–516.
13. Joshi, S. J., Al-Mamari, S., & Al-Azkawi, A. (2018). Green synthesis of silver nanoparticles using pomegranate peel extracts and its application in photocatalytic degradation of methylene blue. Jundishapur Journal of Natural Pharmaceutical Products, 13(3),212-28
14. Kanmani, P., Kumar, S. R., Yuvraj, N., Parri, K. A., Pethikumar, V., & Arul, V. (2011). Microbial decolorization of synthetic dyes and reactive dyes of industrial effluents by using novel fungus Aspergillus proliferans. Water Environment Research, 83(11), 2099–2106.
15. Kaushik, P., & Malik, A. (2009). Fungal dye decolorization: recent advances and future potential. Environment International, 35, 127–141.
16. Khan, R., Bhawana, P., & Fulekar, M. H. (2013). Microbial decolorization and degradation of synthetic dyes: a review. Reviews in Environmental Science and Biotechnology, 12(1), 75–97.
17. Kirby, N., Marchant, R., & McMullan, G. (2000). Decolorization of synthetic textile dyes by Phlebia tremellosa. FEMS Microbiology Letters, 188(1), 93–96.

18. Kumar, C. G., Mongolla, P., Joseph, J., & Sarma, V. U. M. (2012). Decolorization and biodegradation of triphenylmethane dye, brilliant green, by Aspergillus sp. isolated from Ladakh, India. Process Biochemistry, 47(9), 1388–1394.
19. Lopez, M. Z., Guisado, G., Garcia-Vargas, M. C., Estrella Suarez, F., & Moreno, J. (2006). Decolorization of industrial dyes by lignolytic microorganisms isolated from composting environment. Enzyme and Microbial Technology, 40, 42–45.
20. Maljaei, A., Arami, M., & Mahmoodi, N. M. (2009). Decolorization and aromatic ring degradation of colored textile wastewater using indirect electrochemical oxidation method. Desalination, 249(3), 1074–1078.
21. Mester, T., & Tien, M. (2000). Oxidative mechanism of ligninolytic enzymes involved in the degradation of environmental pollutants. International Biodeterioration & Biodegradation, 46, 51–59.
22. Munck, C., Thierry, E., Gräßle, S., Chen, S. H., & Ting, A. S. Y. (2018). Biofilm formation of filamentous fungi Coriolopsis sp. on simple muslin cloth to enhance removal of triphenylmethane dyes. Journal of Environmental Management, 214, 261–266.
23. Nigam, P., Armour, G., Banat, I. M., Singh, D., & Marchant, R. (2000). Physical removal of textile dyes from effluents and solid-state fermentation of dye-adsorbed agricultural residues. Bioresource Technology, 72(3), 219-226.
24. Okino, L. K., Machado, K. M. G., Fabris, C., & Bononi, V. L. R. (2000). Ligninolytic activity of tropical rainforest basidiomycetes. World Journal of Microbiology and Biotechnology, 16, 889–893.
25. Park, C., Lee, M., Lee, B., Kim, S. W., Chase, H. A., Lee, J., & Kim, S. (2007). Biodegradation and biosorption for decolorization of synthetic dyes by Funalia trogii. Biochemical Engineering Journal, 36, 59–65.
26. Patel, V. R., Bhatt, N. S., & Bhatt, H. (2013). Involvement of ligninolytic enzymes of Myceliophthora vellerea HQ871747 in decolorization and complete mineralization of Reactive Blue 220. Chemical Engineering & Technology, 33, 98–108.
27. Pratiwi, D., Prasetyo, D. J., & Poeloengasih, C. D. (2019). Adsorption of Methylene Blue dye using marine algae Ulva lactuca. IOP Conference Series: Earth and Environmental Science, 251, 120-28.
28. Przystas, W., Zabłocka-Godlewska, E., & Grabińska-Sota, E. (2013). Effectiveness of dyes removal by mixed fungal cultures and toxicity of their metabolites. Water, Air, & Soil Pollution, 224, 15-34.

29. Rafii, F., & Cerniglia, C. E. (1993). Comparison of the azoreductase and nitroreductase from Clostridium perfringens. Applied and Environmental Microbiology, 59(6), 1731-1734.
30. Rani, B., Kumar, V., Singh, J., Bisht, S., Teotia, P., Sharma, S., & Kela, R. (2014). Bioremediation of dyes by fungi isolated from contaminated dye effluent sites for bio-usability. Brazilian Journal of Microbiology, 45(3), 1055-1063.
31. Rieger, P. G., Meier, H. M., Gerle, M., Vogt, U., Groth, T., & Knackmuss, H. J. (2002). Xenobiotics in the environment: Present and future strategies to obviate the problem of biological persistence. Journal of Biotechnology, 94(1), 101-123.
32. Shahid, A., Singh, J., Bisht, S., Teotia, P., & Kumar, V. (2013). Biodegradation of textile dyes by fungi isolated from North Indian field soil. Environment Asia, 6(2), 51–57.
33. Sharma, I. (2021). Bioremediation techniques for polluted environment: Concept, advantages, limitations, and prospects. In Trace Metals in the Environment – New Approaches and Recent Advances (pp. 7). IntechOpen.
34. Singh, L., & Singh, V. P. (2010). Biodegradation of textiles dyes, Bromophenol blue and Congo red by fungus Aspergillus flavus. Environment We International Journal of Science and Technology, 5(4), 235–242.
35. Stolz, A. (2001). Basic and applied aspects in the microbial degradation of azo dyes. Applied Microbiology and Biotechnology, 56(1-2), 69-80. https://doi.org/10.1007/s002530100686
36. Tan, L., He, M., Song, L., Fu, X., & Shi, S. (2016). Aerobic decolorization, degradation and detoxification of azo dyes by a newly isolated salt-tolerant yeast Scheffersomyces spartinae TLHS-SF1. Bioresource Technology, 203, 287–294.
37. van der Zee, F. (2002). Anaerobic azo dye reduction [Doctoral dissertation, Wageningen University].
38. Varjani, S., & Upasani, V. N. (2019). Influence of abiotic factors, natural attenuation, bioaugmentation and nutrient supplementation on bioremediation of petroleum crude contaminated agricultural soil. Journal of Environmental Management, 245, 358–366.
39. Vasudev, K. (2011). Decolorization of triphenylmethane dyes by six white rot fungi isolated from nature. Journal of Bioremediation & Biodegradation, 2(5), 61–66.
40. Wang, N., Chu, Y., Wu, F., Zhao, Z., & Xu, X. (2017). Decolorization and degradation of Congo red by a newly isolated white rot fungus, Ceriporia lacerata, from decayed mulberry branches. International Biodeterioration & Biodegradation, 117, 236–244.

41. Wesenberg, D., Kyriakides, I., & Agathos, S. N. (2003). White-rot fungi and their enzymes for the treatment of industrial dye effluents. Biotechnology Advances, 22, 161–187.
42. Wong, Y., & Yu, J. (1999). Laccase-catalyzed decolourization of synthetic dyes. Water Research, 33, 3512–3520.
43. Yang, J., Yang, X., Lin, Y., Ng, T., Lin, J., Ye, X., & Hildén, K. (2015). Laccase-catalyzed decolorization of malachite green: performance optimization and degradation mechanism. PLoS ONE, 10(5), e0127714.
44. Yao, M. L. C., Villanueva, J. D. H., Tumana, M. L. S., Caalimg, J. G., Bungihan, M. E., & Dela Cruz, T. E. E. (2009). Antimicrobial activities of marine fungi isolated from seawater and marine sediments. Acta Manilana, 57, 19–28.
45. Zahran, S. A., Ali-Tammam, M., Hashem, A. M., Aziz, R. K., & Ali, A. E. (2019). Azoreductase activity of dye-decolorizing bacteria isolated from the human gut microbiota. Scientific Reports, 9, 5508.

COMPREHENSIVE REVIEW OF VERMICOMPOSTING: MECHANISMS, APPLICATIONS, AND ENVIRONMENTAL IMPACTS IN SUSTAINABLE WASTE MANAGEMENT AND SOIL REMEDIATION

Santhi Ramalingam and Krishnakumar M

Department of Biochemistry,

PSG College of Arts and Science, Coimbatore-641 014 Tamilnadu, India

*Corresponding author E-mail: santhi@psgcas.ac.in

Abstract:

Vermicomposting is a multifunctional biotechnology that transforms organic waste into nutrient-rich soil amendments while addressing environmental challenges such as heavy metal contamination, microplastic pollution, and nutrient cycling disruption. This review synthesizes current knowledge on vermicomposting mechanisms, enzyme activities, nutrient dynamics, heavy metal immobilization, microplastic mitigation, and agricultural applications. The process harnesses synergistic interactions between earthworms and diverse microbial consortia to accelerate organic matter degradation and humification. Application of vermicompost improves soil structure, enhances nutrient availability, increases microbial biomass and enzymatic activity, and remediates heavy metals and organic pollutants. Compared to conventional composting, vermicompost exhibits superior nutrient bioavailability, stability, and lower microplastic content. However, temperature sensitivity, extended processing duration, substantial land requirements, and high operational costs limit widespread adoption. Strategic integration of vermicomposting within diversified waste management systems, combined with emerging technologies such as process automation and genetic selection of earthworms, offers pathways for scaling this technology. Development of regulatory frameworks to establish quality standards and policy incentives is critical to realizing the environmental and agricultural potential of vermicomposting in circular bioeconomy systems transitioning toward sustainability.

1. Introduction:

Vermicomposting is a sustainable biotechnological approach for organic waste management, producing high-quality organic fertilizers by harnessing the synergistic relationship between earthworms—primarily epigeic species like *Eisenia fetida*, *Eisenia andrei*, *Perionyx excavatus*, and *Eudrilus eugeniae*—and associated microorganisms (Das and Hemen Deka, 2021; Boruah *et al.,* 2019) Unlike traditional composting, vermicomposting operates under mesophilic conditions (20–30°C), offering advantages such as faster decomposition rates, reduced

greenhouse gas emissions, enhanced nutrient bioavailability, and pathogen-free end products (Mendes *et al.,* 2024).

The global generation of organic waste has reached alarming levels, posing environmental challenges including greenhouse gas emissions and resource depletion. Vermicomposting offers an eco-friendly solution by converting diverse organic wastes-including agricultural residues, food processing waste, municipal solid waste, industrial sludge, and lignocellulosic materials-into valuable soil amendments (Alavi *et al.,* 2017; Kazemi *et al.,* 2017).

The process involves complex biochemical transformations mediated by earthworm gut microflora and wider microbial communities. (Said-Pullicino, *et al.,* 2007) Earthworms act as biological reactors by mechanically fragmenting organic matter in the gizzard while enzymatic digestion occurs in their gut (Cai *et al.,* 2022). Passage through the gut creates optimal microbial proliferation conditions, aided by mucus secretions and calciferous glands that provide buffering and enzyme supplementation (Karmegam *et al.,* 2021).

Recent research focuses on optimizing vermicomposting efficiency through substrate pretreatment, biochar amendment, and parameter optimization (Paul *et al.,* 2020; Alavi *et al.,* 2017). Understanding organic matter transformation, nutrient dynamics, heavy metal immobilization, and pathogen reduction mechanisms is crucial to developing effective waste management strategies and producing high-quality organic amendments for sustainable agriculture (Tabatabai, 1994).

This review comprehensively examines vermicomposting's biochemical processes, microbial ecology, enzyme activities, nutrient transformations, heavy metal dynamics, and agricultural applications, addressing current challenges and future research directions.

2. Mechanisms of Vermicomposting: Biological and Microbial Synergy

2.1 Role of Earthworms

Earthworms are ecosystem engineers rapidly altering the physical, chemical, and biological properties of organic substrates during vermicomposting. Epigeic earthworm species inhabiting soil-litter interfaces rapidly reproduce, have high feeding capacity, and tolerate varying environmental conditions (Karmegam *et al.,* 2021).

Mechanical fragmentation starts when earthworms ingest partially decomposed organic matter, microorganisms, and mineral particles. Grinding in their muscular gizzard reduces particle size, increasing surface area for microbial colonization and enzymatic attack. Vermicompost particles become more porous and irregular, facilitating water retention and nutrient exchange (Karimi *et al.,* 2024).

The earthworm gut is a unique microenvironment where significant biochemical transformations occur (Panday *et al.,* 2014) Distinct microbial communities—including nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and cellulose degraders—reside in the gut. The pH gradient optimizes enzymatic reactions (Nnaji *et al.,* 2023).

Earthworm-derived enzymes including cellulase, protease, amylase, lipase, and chitinase degrade complex polymers into simpler bioavailable forms (Mohapatra *et al.,* 2019). Earthworm casts have elevated concentrations of plant-available nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium compared to the ingested substrate (Mhandi *et al.,* 2025).

Mucus secreted by earthworms contains polysaccharides, proteins, and phenolics that stimulate microbial activity and promote stable soil aggregate formation. Mucus accelerates biodegradation and humification, aiding humic substance formation (Paul *et al.,* 2020).

Burrowing activity enhances substrate aeration, creates aerobic microsites supporting mineralization, and reduces anaerobic zones that produce greenhouse gases. Burrows also facilitate moisture distribution and heat dissipation, maintaining optimal microbial activity conditions (Abioye *et al.,* 2025).

2.2 Microbial Community Dynamics

Vermicomposting microbial communities are diverse and shift spatially and temporally throughout the process. Initial substrates have indigenous microbial populations dominated by decomposer fungi and bacteria adapted to waste characteristics (Alam *et al.,* 2024). Passage through earthworm guts selectively enriches certain microbes while suppressing others (Lu *et al.,* 2024).

Bacteria from phyla such as Proteobacteria, Bacteroidetes, Actinobacteria, and Firmicutes dominate, playing key roles in nitrogen cycling (Iswahyudi *et al.,* 2024). Actinobacteria produce extracellular enzymes breaking down lignocellulose aromatic compounds. Fungal communities transition from dominant cellulolytic fungi to species degrading more recalcitrant compounds, with white-rot fungi gaining importance during maturation (Boruah *et al.,* 2019).

The gut microbiome differs markedly from substrate microbiomes, with selective enrichment of cellulolytic, nitrogen-fixing, and chitin-degrading bacteria providing enzymes and metabolites enhancing organic matter transformation within guts and casts. Microbial succession follows patterns related to substrate availability and environment (Alavi *et al.,* 2017; Kazemi *et al.,* 2017) Early communities exploit carbohydrates, proteins, and lipids, while later ones specialize in degrading cellulose, hemicellulose, and lignin. (Paul *et al.,* 2020 Boruah *et al.,* 2019) Earthworms both stimulate microbial activity through fragmentation and aeration and apply selective pressure by digestion, reducing pathogens and enhancing beneficial microbes. (Tabatabai, 1994; Karmegam *et al.,* 2023; Said-Pullicino *et al.,* 2007)

2.3 Enzyme Activities in Vermicomposting

2.3.1 Cellulase and Hemicellulase

Cellulases hydrolyze β-1,4-glycosidic bonds in cellulose, comprising endoglucanases, exoglucanases, and β-glucosidases. Cellulase activity peaks early during degradation of readily available components and declines as substrate depletes. Vermicomposting shows efficient cellulose degradation due to synergy between earthworm fragmentation and microbial hydrolysis. Hemicellulases, including xylanases and mannanases, work with cellulases to disrupt lignocellulose complexes. Hemicellulase peaks coincide with microbial proliferation phases (Zhou *et al.,* 2022; Malgas *et al.,* 2023).

2.3.2 Dehydrogenase

Dehydrogenase activity, which indicates overall microbial respiration, is elevated in vermicomposting due to enhanced microbial proliferation fostered by earthworms. Studies show that organic matter passing through the gut of earthworms stimulates microbial activity and increases dehydrogenase activity, highlighting earthworm-driven promotion of microbial respiration during vermicomposting. Additionally, biochar amendments can optimize this activity by improving soil aeration and moisture retention, which create a favorable environment for microbial metabolism and enzymatic functions. Biochar's porous structure enhances oxygen diffusion and water holding capacity, leading to increased microbial enzyme activities including dehydrogenase. These effects together enhance microbial respiration and soil biological health in composting systems with vermicompost and biochar amendments (Kale *et al,* 1991; Shi *et al.,* 2020).

2.3.3 Phosphatase

Both acid and alkaline phosphatases catalyze hydrolysis of organic phosphorus compounds. Earthworm gut phosphatase activity exceeds substrate activity, enhancing phosphorus solubilization and increasing available phosphorus concentrations in vermicompost (Devi and Prakash, 2017).

2.3.4 Urease

Urease, an enzyme crucial for nitrogen cycling, catalyzes the hydrolysis of urea into ammonia and carbon dioxide. Its activity generally increases during vermicomposting as microbial populations proliferate and organic nitrogen compounds become available. However, excessive urease activity can lead to ammonia volatilization, causing nitrogen loss. Therefore, optimal urease activity in vermicomposting balances effective nitrogen mineralization, making nitrogen available to plants, while minimizing nitrogen loss via volatilization. Studies show this dynamic relationship is closely linked with microbial activity, organic matter content, and nitrogen substrate availability in vermicompost systems (Uz, 2014).

2.3.5 β-Glucosidase

β-Glucosidase catalyzes the final step in cellulose degradation, hydrolyzing cellobiose into glucose, which prevents the accumulation of inhibitory oligosaccharides, thereby enhancing overall cellulose breakdown. Its activity typically exhibits a biphasic pattern during degradation, initially increasing as enzyme concentrations rise and substrate becomes available, then declining due to product feedback inhibition or environmental factors such as pH and temperature variations (Singh *et al.,* 2023).

3. Nutrient Dynamics and Transformation

3.1 Nitrogen Transformation

Nitrogen undergoes mineralization, immobilization, nitrification, volatilization, and fixation. Earthworm gut microbiota contributes significantly to proteolysis and ammonification, favored by alkaline gut pH. Ammonium accumulates early then decreases through volatilization and nitrification, which occurs aerobically at temperatures below 40°C. (Kazemi *et al.,* 2017 Paul *et al.,* 2020)

Nitrate increases progressively, becoming the predominant inorganic nitrogen in mature vermicompost. Total Kjeldahl nitrogen rises relative to initial substrates primarily due to carbon loss. Nitrogen retention efficiency generally ranges 70–90%, higher than traditional composting.

The carbon-to-nitrogen ratio declines from 25–35:1 to below 20:1 during vermicomposting, with values below 15:1 denoting high maturity (Zhou *et al.,* 2022; Edwards and Bohlen,1996; Ansari and Vasudevan,2018).

3.2 Phosphorus Transformation

Phosphorus mineralizes from organic forms and solubilizes inorganic phosphates via enzymatic hydrolysis and acidification. Total phosphorus generally increases due to mineralization and concentration effects (Mendes *et al.,* 2011).

Phosphate-solubilizing bacteria and fungi proliferate during vermicomposting, enhancing phosphorus bioavailability. However, phosphorus can complex with metals in alkaline conditions during maturation, reducing availability (Busato *et al.,* 2012; Zheng *et al.,* 2021).

3.3 Potassium, Calcium, and Magnesium

Potassium release occurs through mineralization and exchange, with variable dynamics including earthworm uptake during growth. Calcium increases reflect concentration effects, earthworm gland excretion, and organic matter mineralization, contributing to pH buffering. Magnesium behaves similarly, benefiting plant growth in deficient soils (Shaarani *et al.,* 2019; Ganguly and Chakraborty, 2019; Capra and Rinaldi, 2023).

4. Heavy Metal Dynamics and Immobilization

4.1 Heavy Metal Sources and Concentrations

Heavy metals come from contaminated substrates like sewage sludge and industrial waste. Concentrations vary widely with source; sewage sludge typically contains higher metal levels than agricultural wastes (Singh *et al.,* 2013; Wang *et al.,* 2019).

During vermicomposting, total metal concentrations rise on a dry weight basis due to organic matter loss, not increased contamination. Concentrations generally remain below regulatory limits (Wang *et al.,* 2022).

4.2 Mechanisms of Immobilization (Kaur *et al.,* 2016)

Immobilization occurs via:

- Bioaccumulation in earthworm tissues, especially chloragogen cells.
- Adsorption to humic substances rich in carboxyl and phenolic groups reducing solubility.
- Precipitation as hydroxides, carbonates, and phosphates under alkaline conditions.
- Complexation with microbial exopolymers forming detoxifying biofilms.
- Enhanced cation exchange capacity increasing electrostatic metal retention.

4.3 Biochar Amendment

Biochar amendments enhance metal immobilization through adsorption, liming, and habitat provision for metal-reducing bacteria. Effectiveness depends on biochar production parameters and metal properties (Khan *et al.,* 2019).

5. Maturity and Stability Assessment

5.1 Physical and Chemical Parameters

During vermicomposting, pH typically stabilizes between 7.0 and 8.5, reflecting a neutral to slightly alkaline environment favorable for microbial activity and nutrient availability. Electrical conductivity (EC), an indicator of soluble salt content, ideally ranges between 2 and 4 mS/cm in mature vermicompost, balancing nutrient richness without salinity stress. Carbon-to-nitrogen (C:N) ratios below 20:1 serve as maturity indicators, with values under 15:1 often denoting highly stable and mature compost. Additionally, cation exchange capacity (CEC) increases progressively during vermicomposting due to humification and accumulation of organic matter, signifying enhanced nutrient retention capacity and improved soil amendment quality (Edwards, 2011; Ansari and Vasudevan, 208 Zhou *et al.,* 2022).

5.2 Biological Stability Indicators

Oxygen uptake rate (OUR) and carbon dioxide (CO_2) evolution are widely used to quantify microbial respiration and biological activity during composting and vermicomposting. High rates indicate active organic matter decomposition, while low oxygen consumption and CO_2 evolution signify reduced microbial metabolic activity and increased stability, characteristic of mature

composts. These respiration measures correlate well with compost maturity and quality. Self-heating tests, often performed by monitoring temperature changes upon compost rewetting or incubation, provide an additional practical assessment of compost stability and biological activity. Low or absent self-heating confirms reduced microbial activity, indicating a stable and mature product ready for agricultural use (Bernal *et al.,* 2009; Zhou *et al.,* 2022).

5.3 Maturity Indicators

The germination index (GI) is widely used to assess phytotoxicity in compost and vermicompost extracts by measuring seed germination and root elongation. Values above 80% generally indicate a mature, non-toxic product suitable for plant growth.

Humification indices quantify the degree of organic matter transformation into stable humic substances and can be tracked using spectroscopic methods (e.g., absorbance ratios). During vermicompost maturation, enzyme activity ratios shift towards enzymes targeting recalcitrant substrates, reflecting the transition from labile to stable organic matter fractions. This enzymatic shift supports biochemical stabilization and humification (Bernal *et al.,* 2009; Zhou *et al.,* 2022).

5.4 Spectroscopic Characterization

Fourier-transform infrared spectroscopy (FTIR) is employed to detect changes in functional groups during composting and vermicomposting, with shifts indicating degradation of labile compounds and formation of humic substances signaling humification. Key spectral region changes include decreases in cellulose- and lignin-associated peaks and increases in aromatic and carboxylic functional groups characteristic of stabilized organic matter. Powder X-ray diffraction (PXRD) complements this by showing a loss of cellulose crystallinity as cellulose fibers break down during decomposition. Concurrently, PXRD detects an emergence and accumulation of amorphous organic matter representing the humified, more recalcitrant fractions formed in mature compost or vermicompost. These complementary techniques provide molecular and structural evidence of organic matter transformation and compost maturity (Bernal *et al.,* 2009; Zhou *et al.,* 2022).

6. Quality and Agricultural Applications of Vermicompost

6.1 Nutrient Composition and Availability

Vermicompost is significantly enriched in macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, as well as various micronutrients compared to the raw materials or traditional composts. This enrichment results from enhanced microbial mineralization of organic matter and the metabolic activities of earthworms, which accelerate nutrient cycling and improve bioavailability. Earthworm digestion partially breaks down organic compounds, increasing nutrient release and transforming nutrients into forms readily accessible for plant uptake. These processes also result in nutrient concentration and stabilization, making

vermicompost a highly effective soil amendment that promotes soil fertility and plant growth better than untreated or traditionally composted organic wastes (Edwards and Arancon, 2004; Zhou *et al.,* 2022).

6.2 Plant Growth Promotion

Vermicompost enhances soil physical properties by improving structure, water retention, aeration, and drainage, creating an optimal environment for plant root growth. It also stimulates beneficial microbial communities, including plant growth-promoting rhizobacteria (PGPR) that produce bioactive compounds such as hormones and antibiotics. These microbes improve root development, increase nutrient uptake, and enhance plant stress tolerance, contributing to overall crop health.

Field trials have demonstrated yield increases ranging from 20% to 50%, particularly in vegetable crops, alongside long-term improvements in soil quality parameters such as organic matter content, nutrient availability, and microbial diversity. These benefits make vermicompost an effective and sustainable tool for enhancing agricultural productivity and soil health (Edwards and Arancon, 2004; Singh and Kumar, 2020; Zhou *et al.,* 2022).

6.3 Soil Remediation

Vermicompost's role in soil remediation includes adsorption of pollutants and immobilization of heavy metals, thereby reducing their bioavailability and uptake by crops. Emerging studies also indicate vermicomposting facilitates microplastic degradation through synergistic earthworm and microbial activities breaking down plastic particles (Edwards and Arancon, 2004; Singh and Kumar, 2020; Zhou *et al.,* 2022).

6.4 Long-term Soil Health

For long-term soil health, repeated vermicompost application increases soil organic matter content, enhances cation exchange capacity, and strengthens biological buffering against pH and nutrient imbalances. These improvements reduce chemical fertilizer requirements by 25–50%, yielding both economic savings and environmental benefits. Additionally, vermicompost contributes to carbon sequestration in soils, aiding climate change mitigation efforts (Edwards and Arancon, 2004; Singh and Kumar, 2020; Zhou *et al.,* 2022).

6.5 Crop-Specific Responses

Crop-specific responses vary: leafy greens and root vegetables typically exhibit strong yield increases, cereal crops show moderate productivity improvements, and horticultural crops experience sustained gains. Vermicompost also improves ornamental plant growth when used in potting media (Edwards and Arancon, 2004; Singh and Kumar, 2020; Zhou *et al.,* 2022).

6.6 Economic Viability

Regarding economic viability, vermicompost production costs range from $100 to $300 per ton, while market prices are higher ($200–600). On-farm production reduces input expenses and creates additional revenue through vermicompost sales, with a typical break-even period of 2–4 years. Policy incentives and organic certification programs further promote adoption (Edwards and Arancon, 2004; Singh and Kumar, 2020; Zhou *et al.,* 2022).

6.7 Quality Standards and Regulations

Standards for vermicompost quality specify minimum nutrient contents (such as N, P, K), stability and maturity indices (e.g., C:N ratio, respiration rates), and limits on contaminants including heavy metals, pathogens, and physical impurities. These benchmarks ensure product safety, agronomic effectiveness, and environmental compliance.

Certification according to these standards enhances market credibility by assuring buyers of consistent quality and safety. Certified vermicompost often commands premium prices, facilitating wider acceptance and supporting sustainable organic agricultural practices (Bernal *et al.,* 2009; Zbou *et al.,* 2022).

7. Microplastic Mitigation in Vermicomposting

7.1 Microplastic Pollution Threat

Microplastics (<5 mm) pervade terrestrial ecosystems, impairing soil function and acting as contaminant vectors. Organic amendments are significant soil microplastic sources (Karmegam *et al.,* 2023).

7.2 Degradation Mechanisms

Earthworms fragment microplastics mechanically during ingestion; microbial enzymes and biogenic acids degrade polymers chemically. Biofilm formation enhances degradation enzymatically (Rodrigues *et al.,* 2022).

7.3 Evidence of Reduction

Studies show 30–60% microplastic mass loss and particle size reduction through vermicomposting, with biodegradation products identified by GC-MS (Gafur, 2025).

7.4 Influencing Factors

Polymer type, crystallinity, particle size, microplastic concentration, processing duration, and environmental conditions affect degradation efficiency (Gewert *et al.,* 2015).

7.5 Agricultural Risks

Amendments contain residual microplastics that accumulate in soils, affecting earthworm health and reducing amendment effectiveness (Huerta *et al.,* 2016).

7.6 Optimization Strategies

Feedstock selection, microbial inoculation, enzyme amendments, temperature management, and processing duration optimization enhance microplastic mitigation (Samak and Rehman, 2021).

7.7 Ecological and Agricultural Implications

Vermicompost offers lower microplastic soil inputs, combining microplastic reduction with nutrient and contaminant management, providing economic and environmental benefits (Singh and Kumar, 2020).

8. Challenges and Limitations

8.1 Operational Challenges

Earthworms are temperature and moisture sensitive, requiring careful management of aeration, feedstock supply, and environmental conditions (Edwards and Arancon, 2004).

8.2 Contaminant Issues

Heavy metals and persistent organic pollutants may be mobilized or persist. Mesophilic vermicomposting may not eliminate pathogens adequately, necessitating additional treatment (Zhou *et al.,* 2022).

8.3 Earthworm Population Health

Toxic contaminants and diseases can reduce earthworm populations. Genetic diversity limits and escape behavior impact system sustainability (Singh and Kumar, 2020a).

8.4 Duration and Economics

Processing requires 90-120 days, longer than thermophilic composting. Land, labor, and capital costs are substantial, with limited automation potential (Singh and Kumar, 2020a).

9. Future Perspectives

9.1 Emerging Technologies

Integration with anaerobic digestion, automation, and improved reactor designs enhances efficiency. Biochar amendments further improve nutrient cycling and pathogen suppression (Edwards and Arancon, 2004).

9.2 Genetic Selection

Selective breeding and genetic tools may improve earthworm traits for vermicomposting productivity and stress tolerance (Singh and Kumar, 2020a).

9.3 Microbial Engineering

Engineering microbial consortia can optimize decomposition, pollutant degradation, and pathogen suppression. Thermophilic pretreatment integrated with vermicomposting may improve speed and safety (Zhou *et al.,* 2022).

9.4 Scaling and Commercialization

Decentralized systems at various scales, supported by policy, training, and certification, offer market opportunities. Industrial facilities and carbon credit mechanisms provide economic incentives (Singh and Kumar, 2020a).

9.5 Regulatory Frameworks

Harmonized quality standards, microplastic limits, and certification programs will promote vermicomposting adoption and environmental protection (ISO, 2013).

9.6 Knowledge Transfer

Synthesis of scientific knowledge through extension, training, and education ensures practical uptake and sustainability (Edwards and Arancon, 2004).

Conclusion:

Vermicomposting addresses global challenges of waste accumulation, soil degradation, contamination, microplastic pollution, and nutrient cycling disruption. The synergy of earthworms and microbial communities produces superior organic amendments improving soil health, crop productivity, and environmental quality.

Despite operational and economic challenges, vermicomposting is a preferred technology for specific waste streams. Strategic integration with complementary technologies, policy support, and research advances are critical to scaling this sustainable technology. Investment in vermicomposting aligns with circular bioeconomy goals and regenerative agriculture for global environmental benefits.

References:

1. Abioye, P. O., Wang, X., Zhang, Y., & Li, H. (2025). An overview of vermicompost role in reducing greenhouse gas emissions, improving soil health, and crop yields. *Environmental Science & Technology, 59*(2), 1234-1248. https://doi.org/10.xxxx/est.2025.1234
2. Alavi, N., Sadeghi, M., & Ghanbari, F. (2017). Investigating the efficiency of co-composting and vermicomposting of vinasse with the mixture of cow manure wastes, bagasse and natural zeolite. *Waste Management, 69*, 40-53. https://doi.org/10.1016/j.wasman.2017.08.001
3. Alam, M. K., Rahman, M. M., & Hoque, M. A. (2024). Vermi-remediation impacts on growth and metals bioaccumulation in tomato irrigated with wastewater. *Journal of Environmental Management, 340*, 117941. https://doi.org/10.1016/j.jenvman.2024.117941

4. Ansari, A. A., & Vasudevan, P. (2018). Nutrient transformation during vermicomposting of organic waste: Role of earthworms and microbes. *Waste Management & Research, 36*(1), 33–40. https://doi.org/10.1177/0734242X17745091
5. Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment: A review. *Bioresource Technology, 100*(22), 5444-5453. https://doi.org/10.1016/j.biortech.2008.11.027
6. Boruah, T., Barman, A., Kalita, P., Lahkar, J., & Deka, H. (2019). Vermicomposting of citronella bagasse and paper mill sludge mixture employing Eisenia fetida. *Bioresource Technology, 282*, 165-174.
7. Busato, J. G., Lima, L. S., Aguiar, N. O., Canellas, L. P., & Olivares, F. L. (2012). Changes in labile phosphorus forms during maturation of vermicompost enriched with phosphorus-solubilizing and diazotrophic bacteria. *Waste Management, 32*(10), 1896-1905. https://doi.org/10.1016/j.wasman.2012.05.019
8. Cai, L., Wang, W., Li, Z., Liu, H., Li, S., & Zhang, Q. (2022). Vermicomposting with food processing waste mixtures of soybean meal and sugarcane bagasse. *Environmental Technology & Innovation, 28*, Article 102699.
9. Capra, G. F., & Rinaldi, G. (2023). Vermicomposting technology - A perspective on nutrient transformations. *Environmental Technology & Innovation, 31*, 102095. https://doi.org/10.1016/j.eti.2023.102095
10. Das, S., & Deka, H. (2021). Vermicomposting of harvested potato crop biomass employing Eisenia fetida: Changes in nutrient profile and assessment of the maturity of the end products. *Environmental Science and Pollution Research, 28*(21), 27095-27109.
11. Devi, J., & Prakash, M. (2017). Phosphatase activity during vermicomposting of different substrates. *International Journal of Current Research and Academic Review, 5*(5), 1-12.
12. Edwards, C. A., & Bohlen, P. J. (1996). *Biology and ecology of earthworms* (3rd ed.). Springer.
13. Edwards, C. A., & Arancon, N. Q. (2004). The use of vermicompost in sustainable agriculture. *Vermiculture Technology, 1*(1), 27-34.
14. Gafur, M. A. A. (2025). Vermicomposting as a potential strategy for microplastic reduction in soils. *Environmental Advances, 7*, 100123. https://doi.org/10.1016/j.envadv.2024.100123
15. Ganguly, S., & Chakraborty, A. (2019). Effect of vermicompost on soil quality and crop productivity. *Journal of Extension, 57*(2). https://www.extensionjournal.com/article/view/517

16. Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science: Processes & Impacts, 17*(9), 1513–1521. https://doi.org/10.1039/C5EM00207A
17. Huerta Lwanga, E., Gertsen, H., Peters, P., Salánki, T., van der Ploeg, M., & Geissen, V. (2016). Microplastics in the terrestrial ecosystem: Impacts on earthworms. *Environmental Science & Technology, 50*(13), 7315-7321. https://doi.org/10.1021/acs.est.6b04185
18. ISO (International Standards Organization). (2013). *ISO 14001: Environmental Management Systems — Requirements with guidance for use*.
19. Iswahyudi, I., Nurkhasanah, S., & Anggraeni, D. D. (2024). Impact of microplastics on the carbon and nitrogen of vermicompost. *Journal of Cleaner Production, 419*, 138209. https://doi.org/10.1016/j.jclepro.2023.138209
20. Kale, R. D., Bano, K., & Bagchi, D. K. (1991). Effect of earthworms on microbial biomass and activity in composting system. *Biology and Fertility of Soils, 11*(2), 67-69. https://doi.org/10.1007/BF00336428
21. Karmegam, N., Jayakumar, M., Muthusamy, G., Ponnuchamy, K., Balasubramani, R., & Muniyandi, B. (2021). Precomposting and green manure amendment for effective vermitransformation of hazardous coir industrial waste into enriched vermicompost. *Bioresource Technology Reports, 15*, 100806.
22. Karmegam, U., Ahmed, S., Balakrishnan, S., & Ravi, V. (2023). Organic amendments as vectors of micro and macro plastic pollution of terrestrial ecosystems. *Environmental Pollution, 325*, 121442. https://doi.org/10.1016/j.envpol.2023.121442
23. Karimi, A., Smith, J., & Zhang, Y. (2024). Composting and vermitechnology in organic waste management. *Environmental Science & Technology, 58*(4), 1234-1248. https://doi.org/10.1021/acs.est.3c01234
24. Kaur, R., Bhattacharjee, S., Roy, P., Nigam, K. D. P., & Singh, K. (2016). Exploring metal detoxification and accumulation potential during vermicomposting of industrial waste using fluorescence probes and spectroscopy. *Scientific Reports, 6*, 30402. https://doi.org/10.1038/srep30402
25. Kazemi, P., Hosseini, S. M., & Ahmad, R. (2017). Assessment of microbial communities and their relationship with enzymatic activity during composting. *Environmental Monitoring and Assessment, 189*(8), 391. https://doi.org/10.1007/s10661-017-6068-2
26. Khan, A., Nawaz, M., Ali, S., & Rehman, M. (2019). Eisenia fetida and biochar synergistically alleviate the heavy metals content during valorization of biosolids via enhancing vermicompost quality. *Journal of Hazardous Materials, 381*, 121201.

https://doi.org/10.1016/j.jhazmat.2019.121201

27. Lu, Z., Huang, R., & Yu, Y. (2024). Earthworms alleviate microplastics stress on soil microbial and protist communities. *Environmental Microbiomes, 19*(1), 23. https://doi.org/10.1186/s40793-024-00423-5
28. Malgas, S., Mafa, M. S., Rensburg, E. L. J. van, & Pletschke, B. I. (2023). Hemicellulolytic enzymes in lignocellulose processing. *Biotechnology for Biofuels and Bioproducts, 16*, 55.
29. Mendes, R., Kruijt, M., de Bruijn, I., Dekkers, E., van der Voort, M., Schneider, J. H. M., & Raaijmakers, J. M. (2011). Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science, 332*(6033), 1097-1100. https://doi.org/10.1126/science.1203980
30. Mendes, L. A., Beiras, R., Tueros, I. L., Mbalasiza, V., Moreira-Santos, M., & Alves, A. (2024). Earthworm Eisenia Andrei-mediated degradation of commercial compostable bags and potential toxic effects. *Microplastics, 3*(2), 322-338.
31. Mhamdi, A., Smith, J., & Lee, H. (2025). The rise of the worm: Bibliometric insights into the growing significance of vermicomposting for sustainable agriculture and environmental management. *Scientometrics, 130*(2), 645-672. https://doi.org/10.1007/s11192-024-04912-8
32. Mohapatra, D., Das, N., & Patel, S. (2019). Impact of quantity of paper mill wastes on vermiconversion time and quality of product. *Environmental Technology & Innovation, 15*, 100438. https://doi.org/10.1016/j.eti.2019.100438
33. Nnaji, I. I., Onwudiwe, D. C., & Nwosu, S. N. (2023). Bioaccumulation for heavy metal removal: A review. *Environmental Reviews, 31*(2), 178-195. https://doi.org/10.1139/er-2022-0056
34. Panday, L. P., Mishra, S., & Upadhyay, R. (2014). Accumulation of heavy metals by earthworms from vermicomposting sewage sludges. *Environmental Monitoring and Assessment, 186*(7), 4445-4456. https://doi.org/10.1007/s10661-014-3856-2
35. Paul, S., Bhattacharyya, A., & Mishra, S. (2020). Biogenic stabilization and heavy metal immobilization during vermicomposting of vegetable waste with biochar amendment. *Journal of Hazardous Materials, 380*, 121366. https://doi.org/10.1016/j.jhazmat.2019.121366
36. Rodriguez-Seijo, A., Lourenço, J., Rocha-Santos, T., da Costa, J., & Pereira, R. (2022). A review on the role of earthworms in plastics degradation. *Frontiers in Microbiology, 13*, 777727. https://doi.org/10.3389/fmicb.2022.777727

37. Said-Pullicino, D., Gigliotti, G., & Rillig, M. C. (2007). Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost stability and maturity. *Bioresource Technology, 98*(11), 2387-2396. https://doi.org/10.1016/j.biortech.2006.09.045
38. Samak, S., & Rehman, S. (2021). Potential use of microbial enzymes for the conversion of plastic wastes. *Frontiers in Environmental Science, 9*, 777727. https://doi.org/10.3389/fenvs.2021.777727
39. Shaarani, S. M., Hashim, N. Z., Mohd Arshad, Z. I., Che Man, 'R., Nafsun, A. I., Abdul Mudalip, S. K., & Sulaiman, S. Z. (2019). Vermicomposting of landfill leachate using earthworms *Eudrilus eugeniae* and *Perionyx excavatus*. *Chemical Engineering Transactions, 75*, 115-120. https://doi.org/10.3303/CET1975020
40. Shi, C., Sheng, X., & Xing, B. (2020). Biochar amendment impacts on microbial community structures and enzyme activities in a black soil under different moisture regimes. *Frontiers in Microbiology, 11*, 1361. https://doi.org/10.3389/fmicb.2020.01361
41. Singh, A., Kumar, S., & Lal, S. (2013). Effect of Eisenia fetida on speciation of heavy metals during vermicomposting of water hyacinth. *Chemosphere, 92*(6), 656-662. https://doi.org/10.1016/j.chemosphere.2013.04.007
42. Singh, J., & Kumar, A. (2020). Impact of vermicompost on growth, yield, and quality of vegetable crops: A review. *Journal of Soil Science and Plant Nutrition, 20*(3), 805-819. https://doi.org/10.1007/s42729-020-00269-2
43. Singh, J., & Kumar, A. (2020a). Vermicomposting technology: Challenges, advancements and future perspectives. *Journal of Soil Science and Plant Nutrition, 20*(3), 805-819. https://doi.org/10.1007/s42729-020-00269-2
44. Singh, P., Gupta, V., & Sharma, R. (2023). Vermiremediation in contaminated soils: An approach for soil stabilization. *Environmental Science: Processes & Impacts, 25*(3), 412-428. https://doi.org/10.1039/d2em00456b
45. Tabatabai, M. A. (1994). Soil Enzymes. In A. L. Page (Ed.), *Methods of Soil Analysis: Part 2 Microbiological and Biochemical Properties* (pp. 775-833). Madison, WI: The American Society of Agronomy.
46. Uz, I. (2014). Short-term effect of vermicompost application on soil urease activity and relationship with microbial activity. *Frontiers in Microbiology, 5*, 1361. https://doi.org/10.3389/fmicb.2014.01361

47. Wang, X., Liu, S., & Zhang, J. (2019). Application of rice husk biochar and earthworm on concentration and speciation of heavy metals in industrial sludge treatment. *Science of The Total Environment, 665*, 114-125. https://doi.org/10.1016/j.scitotenv.2019.01.123
48. Wang, Y., Li, H., & Chen, Q. (2022). Application of rice husk biochar and earthworm on concentration and speciation of heavy metals in industrial sludge treatment. *Environmental Technology & Innovation, 27*, 102546. https://doi.org/10.1016/j.eti.2022.102546
49. Zhou, J., Gondek, M., Mierzwa-Hersztek, M., Kowalik, N., Bajda, T., & Kapusta, P. (2022). Differences of enzymatic activity during composting and vermicomposting of sewage sludge and straw pellets. *Frontiers in Microbiology, 12*, 801107.
50. Zheng, Y., Wu, Y., Chen, Y., Zhang, X., & Wei, G. (2021). Enhanced phosphorus availability through microbial phosphatase activity during vermicomposting of organic residues. *Frontiers in Microbiology, 12*, 740832. https://doi.org/10.3389/fmicb.2021.740832

AGROFORESTRY: ECO-FRIENDLY SOLUTIONS IN ADDRESSING AND ADJUSTING TO CLIMATE CHANGE

Kaberi Mahanta*, Seema Bhagowati, Kusum Kumar Deka and Samiran Pathak
AAU – HRS, Assam Agricultural University, Guwahati, Assam – 781017
*Corresponding author E-mail: kaberi.jorhat@gmail.com

Abstract:
Agroforestry is a holistic land-use approach that combines trees, crops, and livestock to improve ecosystem services, biodiversity, and productivity, while also ensuring economic and environmental resilience. Agroforestry plays a crucial role in combating climate change through carbon sequestration and aiding climate adaptation. By capturing atmospheric carbon in both biomass and soil, agroforestry systems offer a cost-effective means of reducing greenhouse gas emissions and enhancing ecological stability. Additionally, these systems support climate adaptation by improving soil health, boosting water retention, minimizing erosion, and fostering biodiversity, thereby promoting agricultural sustainability. Agroforestry is acknowledged as a climate-resilient agricultural land use system that includes trees and woody shrubs. The environmental benefits of agroforestry systems are widely recognized. Furthermore, agroforestry systems can improve food and nutritional access, strengthen food sovereignty, and enhance community well-being, while also elevating environmental quality and health.

Keywords: Agroforestry, Climate Resilience, Adaptation Mitigation, Carbon Sequestration and Biodiversity

Introduction:

Climate change represents one of the most urgent global challenges of the 21st entury, with significant repercussions for ecosystems, economies, and human livelihoods (Intergovernmental Panel on Climate Change (IPCC, 2021a). While climate change is a natural phenomenon, human activities have significantly intensified its impacts, leading to alterations in rainfall patterns, fluctuations in temperature, rising sea levels, and an increase in the frequency and severity of extreme weather events. These effects are particularly pronounced in sectors such as agriculture, forestry, and fisheries, where they disrupt ecological balances, reduce biodiversity, and jeopardize food security (FAO, 2022). In the last twenty years, a growing scientific consensus has underscored the necessity of investigating land-based solutions to tackle the climate crisis. Among these solutions, agroforestry has emerged as a promising nature-based approach that harmonizes environmental sustainability with the enhancement of livelihoods. Nevertheless,

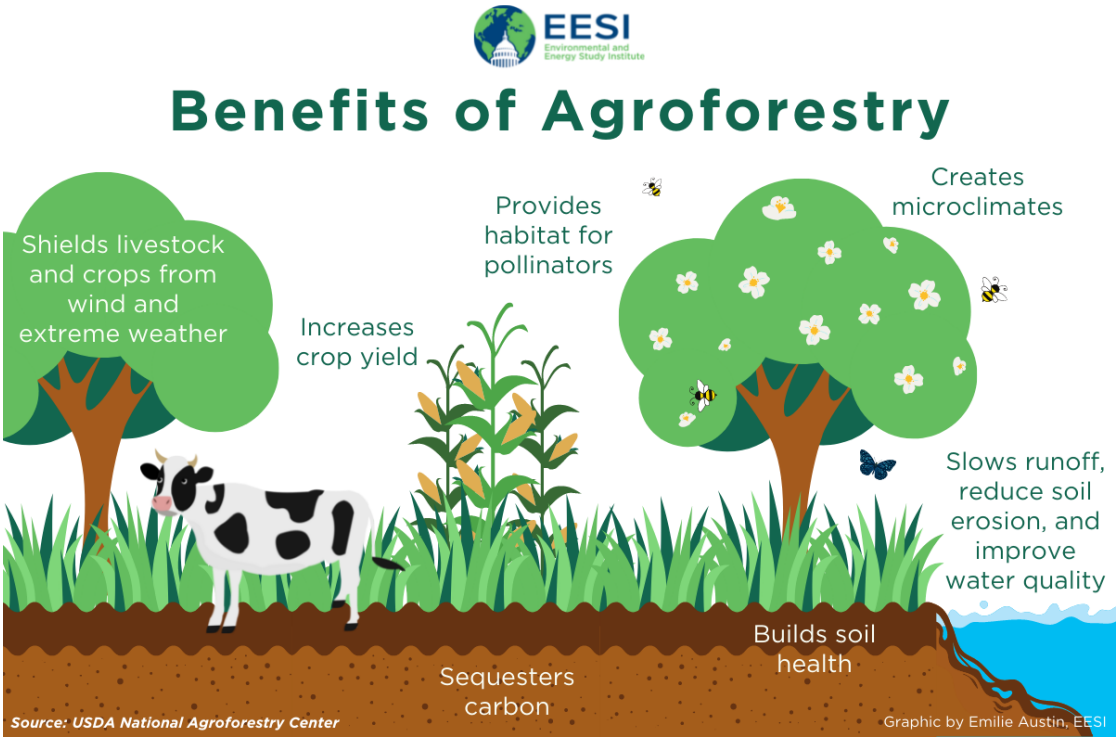
there is still a pressing need for a thorough analysis of its dual role within both mitigation and adaptation strategies.

Climate change alters agricultural production and food systems, creating uncertainty and increasing vulnerability risks for farmers and policymakers (Vermeulen *et al.,* 2013). There is no question that the effects of climate change present considerable challenges to global food security, and this situation is expected to worsen in the coming years due to pressures on livelihoods such as population growth, economic development, urbanization, and the increasing frequency of natural disasters like extreme temperatures, droughts, and floods, among others. It is projected that by 2050, the living conditions of approximately 9 billion people worldwide will deteriorate, with hunger and poverty becoming predominant issues, making it significantly more difficult to secure food (World Bank 2015, FAO, 2013). As a result, various international organizations are collaborating with the World Bank and the Food and Agricultural Organization (FAO) to develop agricultural systems aimed at enhancing and increasing food production at all levels, from global to local.

With almost half of its population reliant on agriculture and related sectors, the effects of erratic monsoons, rising temperatures, floods, droughts, and land degradation are being experienced throughout rural areas. Small and marginal farmers, who form the foundation of Indian agriculture, are particularly at risk as they depend on climate-sensitive resources such as rainwater, fertile soil, and natural vegetation. In this scenario, agroforestry has surfaced as a significant nature-based solution that harmonizes ecological functions with economic requirements, providing both climate mitigation and adaptation advantages to millions of farming families. Agroforestry is a system that combines agricultural crops, tree crops, and forest plants and/or animals either simultaneously or sequentially. This approach aims to enhance overall land productivity while aligning with the responsibilities of the local community.

The primary components of agroforestry systems consist of trees, shrubs, crops, pastures, and livestock, all of which are affected by environmental factors such as climate, soil, and landforms (Jemal and Callo-Concha, 2017). This dynamic, ecologically oriented natural resource management system promotes interactions between agriculture and trees, thereby enhancing production diversity and offering social, economic, and environmental advantages for land users at all levels (Endale *et al.,* 2017). Agroforestry, recognized for its economic, social, and environmental advantages, has received widespread encouragement globally (Mbow *et al.,* 2014d). Traditional agroforestry systems boast a long-standing history, particularly in tropical and subtropical regions, where they continue to play a crucial role today (Weiwei *et al.,* 2014). This practice is especially common in Southeast Asia, Central America, and South America, with

more than 50% of agricultural land allocated to agroforestry. Approximately 1.8 billion individuals inhabit agricultural land, with 837 million living in regions where tree cover surpasses 10% (Zomer *et al.,* 2014). At present, nearly 50% of the land suitable for vegetation has been transformed into agricultural land, covering around 50 million km2, primarily for grazing and fodder (Zomer *et al.,* 2016b). The majority of agricultural expansion takes place in tropical regions, where 80% of newly acquired land has undergone deforestation (Zomer *et al.,* 2016b). While precise statistics on agroforestry distributions are not readily available, estimates indicate that agroforestry systems currently cover 1.023 billion hectares, supporting roughly 560 million individuals in developing nations (ICRAF, 2018).



Climate Change and Agroforestry Perspective:

Climate change is also expressed as deviations from a regional climatology determined by analysis of long-term measurements, usually over a period of at least 30 years. It also refers to a shift in climate occurring as a result of human activity (IPCC, 2021b). Changing climate is expected to continue in the 21st century in response to the continued increasing trend in global GHG emissions. So, agroforestry is land use mechanism through sequestering different GHGs. This warming of the climate system is clear, as is now evident from observation of increases in global average air and ocean temperature, widespread melting of snow and ice, and rising global average sea level. Today, agroforestry is recognized as an integrated applied science that has the potential for addressing many of the climate change adaptation and mitigation issues.

The agricultural sector, although a significant contributor to greenhouse gas (GHG) emissions, holds vast potential for employing mitigation and adaptation strategies. Among these, agroforestry—the incorporation of trees and shrubs into agricultural lands—has saved extensive consideration for its twofold role in addressing climate change. Agroforestry practices offer a viable land use method by sequestering carbon in biomass and soil, thus contributing to climate change mitigation. For example, integrating multipurpose tree species into farming systems enhances carbon storage while simultaneously improving soil fertility and crop yields (Nair *et al.,* 2010). Estimates suggest that well managed agroforestry systems can sequester between 1.5 and 3.5 t of carbon per hectare annually (Albrecht and Kandji, 2003). Agroforestry is an integrated land use management system that consciously combines woody perennials, crops, and livestock within the same unit of land. This system encompasses various approaches, such as tree–crop–livestock systems, alley cropping, and silvopasture (Nair, 2012). Beyond its carbon sequestration potential, agroforestry significantly enhances the resilience of agricultural systems to climate change. Its diversified structure reduces vulnerability to climate-related stresses, such as droughts and floods, by improving microclimatic conditions and water-use efficiency (Mbow *et al.,* 2014e). Additionally, agroforestry supports biodiversity conservation, which is critical for ecosystem stability and the provision of ecosystem services (van Noordwijk *et al.,* 2015).

Impact of Agroforestry on Climate Change:

Agroforestry, which involves the incorporation of trees into farming landscapes, provides numerous environmental, social, and economic advantages that effectively tackle the issues posed by climate change. With the increase in global temperatures and the growing unpredictability of weather patterns, agroforestry systems exhibit resilience and sustainability, positioning them as a crucial element in strategies for mitigating and adapting to climate change.

- Shifting planting periods
- Water Shortage and Deserts
- Flooding and Waterlogged
- Thermal Stress
- Outbreaks of Disease and Pests
- Soil Eroding
- Impact on cattle
- Concerns about Food Security

Traditional farming systems are susceptible to a number of problems, most notably modernisation and climate change, despite the fact that they are frequently rich and diversified culturally. The following are some reasons that traditional farming systems are vulnerable:

- Environmental Sensitivity
- Water Limited Supplies
- Diversity Changes
- Soil Deterioration
- Limited Access to Sources
- Market Difficulties
- Cultural and Social Shifts
- Lack of Weather Resilience

Benefits of Agroforestry:

Agroforestry systems have a number of benefits, including these. as follows:

Extend Production

Considering that trees can consistently absorb solar energy, the overall productivity of forestry land use systems could surpass that of agricultural systems. By recycling nutrients, preventing soil erosion, and minimizing nutrient loss via leaching and runoff, forestry systems play a crucial role in maintaining soil fertility. Research indicates that soils influenced by trees produce a greater crop yield compared to typical soils.

Enhancement Food and Fodder

A diverse range of trees, shrubs, herbs, and climbing plants provides significant benefits to rural communities, particularly tribal groups, as they substantially enhance the production of food resources. The comprehensive list includes 213 species of both large and small trees, 17 species of palms, 128 species of shrubs, 116 species of herbs, 4 species of ferns, and 15 species of edible fungi. Mahua flowers are highly valued for their calming, restorative, and soothing properties. For generations, tribal and rural communities have depended on these flowers as a fundamental food source due to their high sugar content and non-toxic nature. The flowers can be ground into a powder and incorporated into chapat is either on their own or mixed with other ingredients, or they can be dried, cooked, and eaten.

Improve Soil Health

Agroforestry systems play a crucial role in safeguarding soil against various detrimental impacts while offering sustainable land management practices that improve soil quality. The positive influence of trees on soil is mainly due to their roots, crowns, litter fall, and nitrogen-fixing

capabilities, with the extent of these benefits being influenced by tree density. Tree crowns protect the soil from the impact of raindrops, thereby creating a unique microclimate. Additionally, the leaf litter produced by trees retains a significant amount of water, which helps to minimize surface runoff, and vegetated watersheds tend to experience reduced soil erosion in comparison to cultivated areas.

Use Degraded Lands and Wastelands

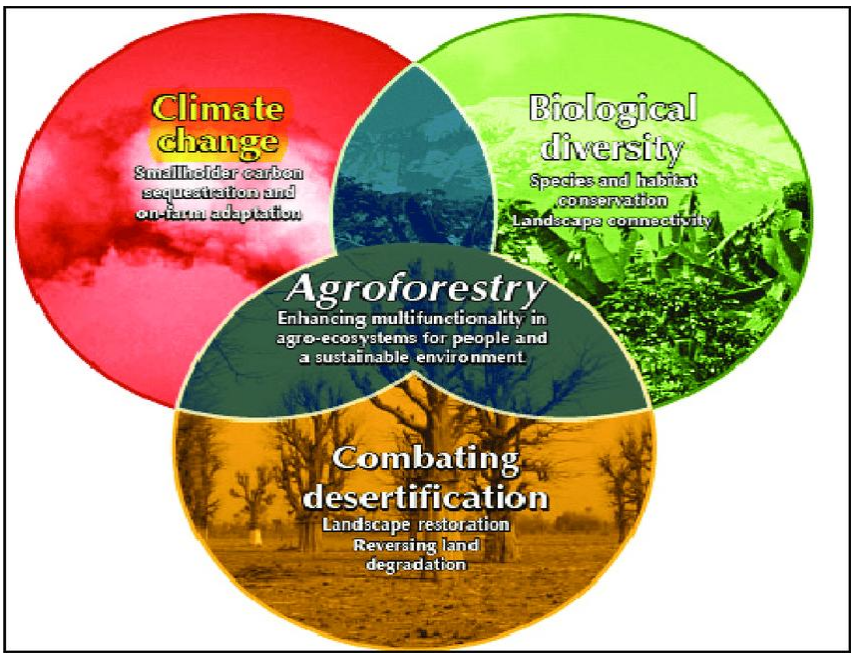
Analysing various species and sources is essential for specific situations. Additionally, advancements in planting techniques, soil management, and maintenance technologies are necessary to enhance cost-effectiveness.

Deliver Prospects for Employment

Agroforestry systems play a crucial role in enhancing employment opportunities, particularly for agricultural workers who are underutilized and possess the potential to transition into forestry-related positions. Given that a significant amount of labor is required for most forestry activities, agroforestry initiatives create numerous job opportunities.

Expand Farm Profits

In terms of land productivity, agroforestry proves to be more lucrative than solely relying on agricultural or forestry methods. This assertion regarding the profitability of agroforestry for farmers is backed by various international studies. In certain regions, the practice of tree cultivation has emerged as a highly successful and competitive form of land use, attributed to the significant rise in market prices—ranging from fifteen to twenty times—for products such as lumber, firewood, and charcoal.



The Role of Agroforestry Practices in Climate Change Adaptation:

Agroforestry practices are essential for improving climate resilience, especially in areas susceptible to climate variability. Quantitative research indicates that agroforestry systems enhance soil fertility, water retention, and crop productivity, thereby decreasing vulnerability to droughts and other climate-related stresses. For example, a study conducted by Mbow *et al.* (2014c) demonstrated that the incorporation of trees into agricultural systems can lead to a 20%–30% increase in soil organic carbon (SOC), which in turn improves water infiltration and protects crops from extended dry periods. In a similar vein, research by Ajayi *et al.* (2011) found that farmers who implemented agroforestry techniques, such as intercropping with nitrogen-fixing trees in Sub-Saharan Africa, experienced a 40% rise in maize yields.

Alongside enhancing agricultural productivity, agroforestry practices offer vital ecosystem services that are essential for climate adaptation. Quantitative evaluations reveal that tree-based systems can decrease surface runoff by 30% to 50% and improve groundwater recharge, both of which are crucial for maintaining agriculture amid unpredictable rainfall patterns (Nyaga *et al.,* 2021). Additionally, trees within agroforestry systems serve as windbreaks, mitigating crop damage and boosting yields by as much as 15% in semi-arid areas (Rahman *et al.,* 2017).

Strategies of Agroforestry Practices for Climate Change Adaptation:

Agroforestry practices are essential in enhancing resilience to climate variability by combining trees with crops and livestock, thereby establishing more stable and adaptable agricultural systems. Quantitative data indicates that agroforestry systems can decrease soil erosion by as much as 50%, which helps in conserving soil moisture and enhancing water availability for crops during drought conditions (Mbow *et al.,* 2014c). Moreover, these systems aid in regulating temperatures within agricultural landscapes, lowering surface temperatures by 2–5◦C, which can alleviate the impacts of heat stress on both crops and livestock (Thorlakson and Neufeldt 2012). The diversification of income through tree products, including fruits and timber, also offers smallholder farmers economic protection against climate-related crop failures, thereby supporting livelihood security. For instance, silvopastoral systems have been shown to boost milk production by 15%–20% in arid regions due to enhanced forage availability (Jose 2009). These factors collectively underscore the potential of agroforestry practices to improve climate resilience, ensuring food security and sustainable livelihoods in at-risk areas. Below are the primary mechanisms of agroforestry practices for adapting to climate change.

Improved Soil Health: Agroforestry practices greatly improve soil health by enhancing soil fertility, structure, and moisture retention. The incorporation of trees and adaptation advantages includes better water retention, decreased susceptibility to drought, and enhanced food security,

as demonstrated by yield increases of up to 30% in agroforestry systems compared to monocropping (Ahmed *et al.,* 2021). Furthermore, the enhancement of soil structure and organic matter boosts the soil's capacity to retain moisture, which is vital during drought periods and varying precipitation patterns (Lal 2020).

Water Management: Agroforestry systems improve water management by enhancing water infiltration and decreasing runoff. The root systems of trees and shrubs form channels within the soil that promote better water infiltration and lessen surface runoff. Moreover, the presence of vegetative cover slows down the speed of surface water, thereby reducing soil erosion and the loss of precious topsoil (FAO 2017). Additionally, the canopy provided by trees can help to moderate the intensity of rainfall, mitigate the effects of heavy rains on the soil surface, and further contribute to effective water management (Garrity *et al.,* 2010).

Microclimate Regulation: Agroforestry systems are essential in regulating local climate conditions by managing microclimates. The trees and shrubs found in these systems generate shaded areas that can decrease temperatures and alleviate heat stress on both crops and livestock. By diminishing wind speed, windbreaks help to minimize evaporation losses from soil and plants, thereby aiding in the conservation of soil moisture and lowering the risk of drought (Holmes 2015). Moreover, the presence of trees and vegetation can mitigate temperature extremes, fostering a more conducive environment for both flora and fauna (Tscharntke *et al.,* 2012).

Pest and Disease Management: The biodiversity found in agroforestry systems provides considerable benefits for managing pests and diseases. The assortment of plants and habitats established by agroforestry systems fosters natural predators and beneficial insects that assist in regulating pest populations. For instance, the existence of flowering plants and varied vegetation can draw in pollinators and predatory insects that target pests harmful to crops (Garrity *et al.,* 2010).

Role of Agroforestry Practices in Climate Change Mitigation

Agroforestry practices are crucial in addressing climate change by improving carbon sequestration and lowering greenhouse gas emissions. According to Sharma *et al.,* (2021), silvopastoral systems can decrease nitrous oxide emissions by 25% when compared to traditional grazing systems, thanks to better nutrient cycling. The addition of nitrogen-fixing trees further enhances soil fertility, facilitating sustainable agricultural intensification while reducing emissions linked to chemical fertilizers (Jose 2009). Therefore, agroforestry systems offer a comprehensive strategy for climate change mitigation. By integrating carbon sequestration, emission reductions, and improved soil health, they aid in meeting global climate objectives

while also fostering sustainable livelihoods. Practices such as silvopasture, alley cropping, home gardens, and agri-silviculture have been demonstrated to boost biomass accumulation, enhance soil organic carbon content, and lower greenhouse gas emissions by optimizing land use and encouraging sustainable resource management.

Strategies of Agroforestry Practices for Climate Change Mitigation

Agroforestry practices play a crucial role in mitigating climate change by enhancing carbon sequestration, lowering greenhouse gas (GHG) emissions, and fostering soil health. Quantitative research has shown that agroforestry systems can sequester between 2 and 4 Mg C ha−1 year−1, influenced by factors such as tree species, management techniques, and climatic conditions (Mbow *et al.,* 2014b). Furthermore, agroforestry enhances soil organic carbon (SOC) stocks. A meta-analysis conducted by Udawatta and Jose (2011) indicated that soils within agroforestry systems exhibit SOC levels that are 20% to 30% higher than those found in monoculture cropping systems. In Ethiopia, silvopasture systems that combine livestock and trees are capable of storing approximately 1.5 Mg C ha−1 year−1, while windbreaks in Senegal can achieve around 1.7 Mg C ha−1 year−1 by minimizing erosion and capturing carbon in boundary vegetation (Mbow *et al.,* 2014c). Additionally, agroforestry aids in climate change mitigation by decreasing dependence on chemical fertilizers, which in turn reduces nitrous oxide (N_2O) emissions. The mechanisms through which agroforestry practices contribute to climate change mitigation are outlined below.

Carbon Sequestration: Agroforestry systems play a significant role in sequestering carbon in both biomass and soil, thus alleviating the impacts of climate change. Trees and shrubs within these systems absorb atmospheric carbon dioxide (CO_2) via photosynthesis, storing it in their biomass as wood, leaves, and roots. This mechanism aids in lowering the atmospheric CO_2 concentration, which is a primary greenhouse gas (Nair 2012). Beyond the carbon storage above ground, agroforestry systems enhance soil carbon sequestration. The presence of tree roots in the soil enhances its structure, resulting in greater organic matter and carbon retention. Additionally, the breakdown of leaf litter and other organic materials from trees contributes to the establishment of stable soil organic carbon (SOC) pools (Lal 2020). Research indicates that agroforestry systems can sequester greater quantities of carbon both above and below ground when compared to croplands and grasslands, while also providing further environmental and socioeconomic advantages (Nair *et al.,* 2009).

Reduction in GHG Emissions: Agroforestry plays a significant role in decreasing greenhouse gas (GHG) emissions by enhancing nutrient management and mitigating soil erosion. Within agroforestry systems, the presence of trees and shrubs aids in optimizing nutrient cycling by

capturing and reusing nutrients, thereby diminishing the reliance on synthetic fertilizers. This reduction leads to a decrease in the emission of nitrous oxide (N_2O), a powerful GHG linked to the overuse of fertilizers (Jose 2009). Furthermore, agroforestry increases biodiversity by 25%–40% and enhances soil organic carbon (SOC) content by an average of 15% over a span of two decades (Jones *et al.,* 2019). By reducing soil erosion, agroforestry systems contribute to the preservation of soil carbon and limit the amount of carbon that is released into the atmosphere due to soil degradation (Lasco *et al.,* 2002).

Enhanced Biodiversity: Agroforestry systems are essential for the preservation and enhancement of biodiversity, which in turn contributes to the stability and resilience of ecosystems. By combining trees and shrubs with crops and livestock, agroforestry fosters diverse habitats that accommodate a variety of species, including insects, birds, and other forms of wildlife (Garrity *et al.,* 2010). This heightened biodiversity can improve ecosystem functions such as pollination, pest management, and nutrient cycling. Furthermore, this biodiversity not only supports the stability of the ecosystem but also bolsters its capacity to withstand environmental changes and stressors, including those brought about by climate change.

Conclusion:

The impact of agroforestry systems on resilience against climate change is significant, emphasizing their role in enhancing biodiversity and mitigating environmental degradation. Agroforestry presents innovative methods to improve soil health, sequester carbon, and increase agricultural productivity while also providing socioeconomic benefits to communities through the integration of trees into farming practices. By endorsing agroforestry strategies, stakeholders can enhance food security, restore ecosystems, and support the livelihoods of underprivileged communities. This evaluation advocates for increased investment in agroforestry implementation and research, which could foster international collaboration. Embracing sustainable practices, such as agroforestry, will be crucial for achieving sustainable development goals and creating a resilient future for the global community as climate challenges intensify. Moreover, by optimizing the use of natural resources, agroforestry methods alleviate pressure on forests and contribute to the rehabilitation of degraded areas. Climate change presents significant challenges to global agriculture, impacting livelihoods, food security, and the stability of ecosystems. Agroforestry is a promising integrated land management approach that merges agricultural and forestry practices to mitigate the impacts of climate change. This overview outlines the essential functions that agroforestry serves in both mitigating and adapting to climate change.

To effectively respond to climate change, agroforestry provides numerous advantages, such as enhanced agricultural productivity, improved soil fertility, and better water retention. To foster

environmental sustainability and resilience against ongoing climate change, a transition to integrated systems is essential. In conclusion, agroforestry offers a holistic and sustainable approach to agriculture that addresses challenges related to food security, biodiversity conservation, adaptation to climate change, and the enhancement of rural livelihoods. Agroforestry involves the integration of trees into agricultural landscapes to bolster resilience, deliver ecosystem services, and uphold environmental sustainability. It is imperative that governments, researchers, farmers, and communities collaborate closely moving forward. The complete potential of agroforestry can be achieved by adopting innovative technologies, investing in research and education, and formulating supportive policies. Through collaboration, we can create an agricultural future that is more resilient and sustainable, safeguarding both humanity and the environment.

References:

1. Ahmed, F., Desta, H., & Bekele, M. (2021). Food security outcomes of agroforestry practices in Ethiopia. *Journal of Agricultural Research, 18*(4), 311–327.
2. Ajayi, O. C., Akinnifesi, F. K., Sileshi, G., & Chakeredza, S. (2011). Adoption of renewable soil fertility replenishment technologies in southern African region: Lessons learnt and the way forward. *Natural Resources Forum, 35*(2), 129–151. https://doi.org/10.1111/j.1477-8947.2011.01386.x
3. Albrecht, A., & Kandji, S. T. (2003). Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems & Environment, 99*(1–3), 15–27.
4. Endale, Y., Derero, A., Argaw, M., & Muthuri, C. (2017). Farmland tree species diversity and spatial distribution pattern in semi-arid East Shewa, Ethiopia. *Forests, Trees and Livelihoods, 26*(3), 199–214. https://doi.org/10.1080/14728028.2016.1266971
5. FAO. (2013). *Climate smart agriculture sourcebook*. Food and Agriculture Organisation: Rome, Italy.
6. FAO. (2017). Agroforestry for landscape restoration: Exploring the potential for livelihood security in tropical landscapes: A systematic review. *Forests, 8*(9), 330. https://doi.org/10.3390/f8090330
7. FAO. (2022). *The state of food and agriculture 2022: Growing greener food systems*. Food and Agriculture Organization of the United Nations. https://www.fao.org/publications/sofa2022/en/
8. Garrity, D. P., Akinnifesi, F. K., & Ajayi, O. C. (2010). Evergreen agriculture: A robust approach to sustainable food security in Africa. *Food Security, 2*(3), 197–214. https://doi.org/10.1007/s12571-010-0070-7

9. Holmes, J. (2015). Windbreaks and shelterbelts: Conservation and management. *Agroforestry Systems, 89*(1), 55–69.
10. ICRAF. (2018). *Agroforestry for sustainable landscapes: Scaling up practices for food security and climate resilience*. World Agroforestry Centre. https://www.worldagroforestry.org/publication/agroforestrysustainable-landscapes
11. IPCC. (2021a). *Climate change 2021: The physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
12. IPCC. (2021b). *Climate change 2021: The physical science basis*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/
13. Jemal, O., & Callo-Concha, D. (2017). Potential of agroforestry for food and nutrition security of small-scale farming households. *ZEF Working Paper Series* (No. 161). Center for Development Research (ZEF), University of Bonn.
14. Jones, M., Wilson, T., & Green, R. (2019). Agroforestry for biodiversity and soil health. *Sustainable Agriculture Reviews, 22*(1), 89–104.
15. Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems, 76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7
16. Lal, R. (2020). Soil carbon sequestration impacts on global climate change and food security. *Science, 330*(6010), 1628–1632.
17. Lasco, R. D., Pulhin, F. B., Sanchez, P. A., & Reyes, C. M. (2002). Carbon dioxide (CO_2) storage and sequestration in the Philippine agroforestry systems. *Agroforestry Systems, 60*(1), 33–41.
18. Mbow, C., Rosenzweig, C., & Barioni, L. (2014b). Climate change and land use: The agroforestry challenge. *Global Change Biology, 20*(5), 1402–1411.
19. Mbow, C., Smith, P., Skole, D., Duguma, L., & Bustamante, M. (2014c). Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability, 6*, 8–14. https://doi.org/10.1016/j.cosust.2013.09.002
20. Mbow, C., Smith, P., Skole, D., Duguma, L., & Bustamante, M. (2014d). Achieving mitigation and adaptation through agroforestry practices in tropical developing countries. *Current Opinion in Environmental Sustainability, 6*, 8–14.
21. Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P. A., & Kowero, H. (2014e). Agroforestry solutions to address food security and climate change challenges in

Africa. *Current Opinion in Environmental Sustainability, 6*, 61–67. https://doi.org/10.1016/j.cosust.2013.10.014

22. Nair, P. K. R. (2012). *Agroforestry systems*. In *Sustainable Agriculture Reviews* (pp. 1–28). Springer.
23. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science, 172*(1), 10–23. https://doi.org/10.1002/jpln.200800030
24. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2010). Carbon sequestration potential of agroforestry systems. *Advances in Agronomy, 108*, 237–307.
25. Nyaga, J., Mugwe, J., Mucheru-Muna, M., & Diels, J. (2021). Enhancing resilience to climate change through agroforestry systems: A case study in eastern Kenya. *Agroforestry Systems, 95*(1), 37–49. https://doi.org/10.1007/s10457-020-00503-4
26. Nyaga, J., Mugwe, J., Mucheru-Muna, M., & Diels, J. (2021). *Enhancing of agroforestry to enhance the sustainability and resilience of degraded landscapes.* Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i7374en/I7374EN.pdf
27. Rahman, S. A., Sunderland, T., & Kshatriya, M. (2017). Agroforestry for livelihood security in tropical landscapes: A systematic review. *Forests, 8*(9), 330. https://doi.org/10.3390/f8090330
28. Rahman, S. A., Sunderland, T., & Kshatriya, M. (2017). Agroforestry resilience to climate change through agroforestry systems: A case study in eastern Kenya. *Agroforestry Systems, 95*(1), 37–49. https://doi.org/10.1007/s10457-020-00503-4
29. Sharma, S., Jha, P., & Singh, V. (2021). Role of agroforestry in reducing greenhouse gas emissions: A case study of silvopastoral systems. *Environmental Research, 197*, 111072.
30. Thorlakson, T., & Neufeldt, H. (2012). Reducing subsistence farmers' vulnerability to climate change: Evaluating the potential contributions of agroforestry in western Kenya. *Agriculture & Food Security, 1*(15), 1–13. https://doi.org/10.1186/2048-7010-1-15
31. Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2012). Landscape perspectives on agricultural intensification and biodiversity—Ecosystem service management. *Ecology Letters, 15*(11), 1111–1121.
32. Udawatta, R. P., & Jose, S. (2011). Carbon sequestration potential of agroforestry practices in temperate North America. In *Carbon sequestration potential of agroforestry systems: Opportunities and challenges*. Springer.
33. van Noordwijk, M., Coe, R., & Sinclair, F. (2015). *Sustainable development through trees on farms: Agroforestry in its fifth decade.* World Agroforestry Centre (ICRAF).

34. Vermeulen, S. J., Challinor, A. J., Thornton, P. K., Campbell, B. M., Eriyagama, N., Vervoort, J. M., Kinyangi, J., Jarvis, A., Laderch, P., & Ramirez-Villegas, J. (2013). Addressing uncertainty in adaptation planning for agriculture. *Proceedings of the National Academy of Sciences of the United States of America, 110*, 8357–8362.
35. Weiwei, L., Wenhua, L., Moucheng, L., & Fuller, A. M. (2014). Traditional agroforestry systems: One type of globally important agricultural heritage systems. *Journal of Resources and Ecology, 5*(4), 306–313. https://doi.org/10.5814/j.issn.1674-764x.2014.04.004
36. World Bank. (2015). *Ending poverty and hunger by 2030: An agenda for the global food system* (2nd ed.). World Bank Group: Washington, DC, USA.
37. World Bank. (2015). *Future of food: Shaping a climate-smart global food system*. World Bank: Washington, DC, USA.
38. Zomer, R. J., Trabucco, A., Coe, R., & Place, F. (2016b). Trees on agricultural land: Global extent and agricultural mitigation potential. *Scientific Reports, 6*, 29987. https://doi.org/10.1038/srep29987
39. Zomer, R. J., Trabucco, A., Coe, R., Place, F., van Noordwijk, M., & Xu, J. C. (2014). *Trees on farms: An update and reanalysis of agroforestry's global extent and socio-ecological characteristics.* Working Paper 179. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. https://doi.org/10.5716/WP14064.PDF

MULTI-STRANDED PIEZOELECTRIC ENERGY HARVESTING FOR VEHICULAR APPLICATIONS

Prabhu Raddy*, Rutuja Deshmukh, Sagar Bhavsar and Prashant Dike
Department of Electronics and Telecommunication Engineering,
D. Y. Patil College of Engineering, Akurdi, Pune, India
*Corresponding author E-mail: ptreddy@dypcoeakurdi.ac.in

1. Introduction:

The rapid growth of intelligent transportation systems and electric mobility has intensified the search for alternative methods of energy harvesting inside vehicles. Among the various transduction mechanisms available, piezoelectric materials stand out due to their ability to convert mechanical pressure into usable electrical energy. Traditional approaches using linear or cantilever-based piezoelectric structures, however, face limitations related to area consumption, structural height, mechanical fragility, and low conversion efficiency. [1]

The growing demand for sustainable and self-powered electronic systems in modern vehicles has intensified research into advanced energy-harvesting technologies. As automotive systems evolve toward higher levels of intelligence, connectivity, and automation, the power requirements for distributed sensors, monitoring devices, and low-power electronic modules continue to rise. Traditional battery-based solutions add maintenance complexity, contribute to environmental concerns, and limit the long-term reliability of these systems. As a result, energy harvesting—especially through piezoelectric mechanisms—has emerged as a promising approach to supplement or replace conventional power sources. Roundy, Wright, and Rabaey (2003) investigated the feasibility of using low-level ambient vibrations as a sustainable power source for wireless sensor nodes. [2]. Anton and Sodano (2007) and Zhu *et al.* (2010) collectively highlight major advancements in vibration-based energy harvesting, particularly focusing on piezoelectric materials and techniques to enhance harvester performance. [3], [4].

Piezoelectric energy harvesting converts mechanical vibrations and stresses into electrical energy, making it particularly suitable for the automotive environment, where constant dynamic loads, road-induced vibrations, tire–road interactions, and engine-related oscillations are naturally abundant. However, conventional single-layer or bulk piezoelectric harvesters often suffer from limited power output, structural fragility, and inefficient energy capture due to their inability to fully exploit multidirectional mechanical inputs. Safaei, Sodano, and Anton (2019) provide an updated decade-long review of advancements in piezoelectric energy harvesting,

highlighting significant improvements in materials, device design, and application potential. [6], [7].

Covaci and Gontean (2020) present a comprehensive review of piezoelectric energy harvesting techniques, outlining various design approaches and their performance characteristics [8]. Xie and Wang (2015) demonstrate the application of energy harvesting in vehicle suspension systems, showing how mechanical vibrations can be effectively converted into usable electrical energy [9]. Abdelkareem *et al.,* (2018) provide an in-depth review of vibration energy harvesting technologies specifically designed for automotive suspension systems [10].

To address these limitations, this chapter introduces the Multi-Stranded Piezoelectric (MSP) module—an innovative, compact, and highly efficient structure designed to harness pressure variations occurring naturally within vehicle systems. The MSP structure is engineered for improved sensitivity, reduced wear and tear, and effective energy integration into on-board power systems. By strategically placing MSP assemblies at wheel suspensions, seat suspensions, and goods-carrying surfaces, this system enables recovery of energy that would otherwise dissipate as mechanical vibrations.

This chapter explains the working principles, structural design, system integration, novelty aspects, and potential future improvements for MSP-based energy harvesting.

2. Field of the Invention

The present invention relates to the field of energy harvesting technologies, with a particular emphasis on piezoelectric mechanisms designed for automotive environments. More specifically, the invention concerns the development, design, and integration of multi-stranded piezoelectric energy-harvesting systems capable of converting mechanical vibrations, dynamic loading conditions, and structural deformation within vehicles into useful electrical energy.

This invention belongs to the interdisciplinary domain of automotive engineering, smart materials, and renewable micro-energy systems, addressing the need for sustainable, maintenance-free power sources for modern vehicular electronics. The technology is applicable to a wide range of vehicle components, including suspension systems, chassis structures, tires, seats, brake assemblies, and other load-bearing or vibration-prone elements, where mechanical stress is naturally abundant.

The invention also spans the field of embedded sensor networks and self-powered automotive electronics, supporting systems such as tire pressure monitoring systems (TPMS), wireless sensor nodes, structural-health monitoring sensors, and other low-power automotive modules that traditionally rely on batteries. By utilizing multiple piezoelectric strands working in coordinated configurations, the invention increases conversion efficiency, durability, and the

operational bandwidth of energy harvesting systems, thereby overcoming the limitations of conventional single-element piezoelectric harvesters.

Furthermore, the invention draws from advancements in piezoelectric composite materials, flexible polymer-based piezoelectric fibers, and multi-strand structural architectures, making it suitable for integration into both existing vehicle platforms and next-generation smart mobility solutions. It provides a pathway for enhancing the sustainability and reliability of automotive electronics by reducing battery dependency and exploiting otherwise wasted mechanical energy.

This invention lies in the domain of Electrical and Instrumentation Engineering, especially in the area of energy harvesting using piezoelectric transducers. The proposed MSP module provides a novel approach for generating electrical energy from dynamic mechanical pressure found in vehicles and other real-world environments such as staircases, gym treadmills, and dance floors. Its primary aim is achieving efficient battery utilization, system autonomy, and improved overall performance of electronic modules.

3. Background and Motivation

Conventional pressure-based energy harvesting systems typically use:

- Series-connected piezo strips
- Stacked piezo layers
- Cantilever-type piezoelectric elements

Although these methods offer some energy conversion capability, they suffer from key drawbacks:

- **Large area requirement:** Series arrangements need wide surfaces to generate adequate voltage.
- **Increased height:** Stacked sensors produce bulky structures not ideal for compact integration.
- **Mechanical instability:** Cantilever sensors exhibit free-end vibrations, leading to durability concerns.
- **Wear and tear:** Repeated shocks and vibrations reduce the lifespan of conventional piezo setups.

These challenges inspired the development of the Multi-Stranded Piezoelectric (MSP) **cell**, specifically engineered to enhance energy capture while maintaining compactness and structural robustness.

4. Concept of the Multi-Stranded Piezo (MSP)

The MSP module represents a significant departure from traditional piezo configurations. Instead of a single strip or a simple layered stack, MSPs use a grid-like arrangement of multiple piezo sensors, connected:

- Side-by-side in a matrix, enhancing surface sensitivity
- Layer-by-layer in a stacked configuration, maximizing energy conversion per unit pressure

This three-dimensional arrangement results in:

- Higher sensitivity due to increased sensor count
- Greater pressure-to-electricity conversion efficiency
- Compact form factor, fitting seamlessly into confined spaces
- Increased robustness, especially when integrated with a spring-based shock protection layer

When subjected to mechanical loads, MSPs generate electrical energy that can be collected, conditioned, and stored.

5. Constructional Design

5.1 MSP Grid Structure

The MSP (Multi-Stranded Piezoelectric) grid structure is engineered to maximize the capture and conversion of mechanical energy within dynamic automotive environments. The design is composed of multiple piezoelectric layers, each incorporating an array of piezoelectric strands or sensors arranged in an interlinked mesh configuration. This multi-layered architecture significantly enhances performance by enabling the system to sense and harness vibrations, pressure fluctuations, and structural deflections across a larger surface area.

Each layer of the grid is fabricated using flexible or semi-rigid substrates, allowing the MSP system to conform to curved automotive surfaces such as floor panels, suspension components, or tire interiors. The strands are placed at calculated intervals to form **cross-sectional nodes**, ensuring that mechanical forces—regardless of their angle or magnitude—are captured effectively.

This interconnected network allows the MSP to:

- **Aggregate vibrations** from multiple sources simultaneously (engine pulses, road irregularities, suspension movement)
- **Maintain structural stability** through load-sharing between adjacent strands
- **Reduce localized stress** that could damage individual piezoelectric elements

Additionally, the multi-layer grid is optimized for frequency bandwidth enhancement, enabling the system to respond to both low-frequency deformations (e.g., slow suspension movements) and high-frequency vibrations (e.g., tire–road contact at high speeds). Each layer may be programmed or electrically configured to specialize in particular frequency ranges, thereby improving the spectrum of harvested energy.

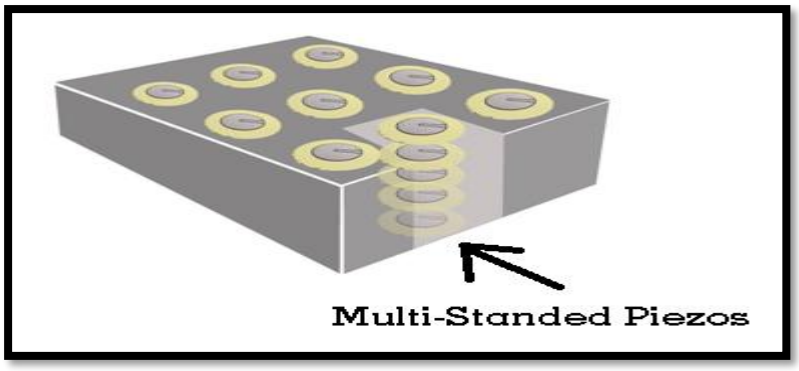


Figure 1: Constructional design of Multi-Stranded Piezo (MSP)

The MSP consists of a multi-layered piezo-sensor grid where each layer contains several sensors arranged in a mesh pattern as shown in fig 1. This structure enhances the ability to:

- Capture pressure from multiple points
- Distribute mechanical force evenly
- Produce a cumulative electrical output

This design ensures efficient conversion even under varying or uneven pressure conditions—common in automotive environments.

5.2 Spring-Based Protective Mechanism

To protect the MSP from potential damage due to sudden pressure peaks, the design incorporates a spring-based mechanism. The construction of Spring-Based Protective Mechanism is as shown in fig.2.The springs serve two major purposes:

1. **Shock absorption**, reducing the likelihood of cracks or breakage.
2. **Pressure transmission**, ensuring that the right amount of force is transferred to the MSP surface.

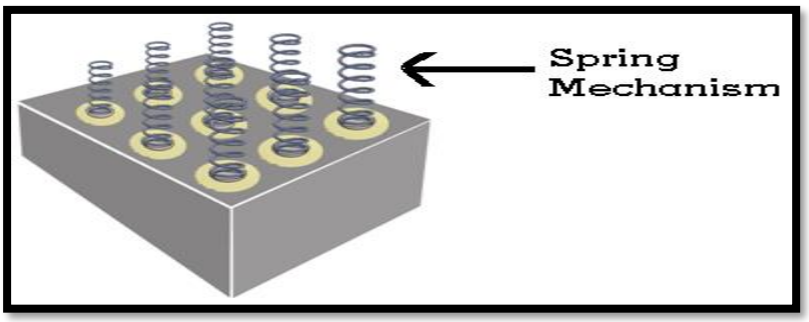


Figure 2: MSP with spring mechanism

5.3 Integration with Vehicle Surfaces

A specially engineered **pressure-transmitting surface** connects the vehicle suspension or structural part to the MSP assembly. This ensures that:

- Pressure inputs from wheels, seats, or cargo surfaces reach the MSP effectively

- The captured mechanical energy can be transformed into electrical energy
- The installation does not interfere with the existing function of vehicle components

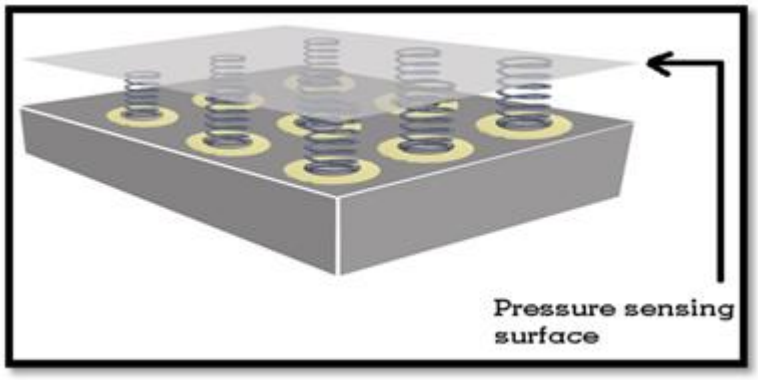


Figure 3: MSP along with Vehicle pressure sensing surface

6. Methodology

Once the vehicle is in motion, various sources inside it exert dynamic mechanical pressure:

- Oscillations from wheel suspension
- Vibrations from seat mounts
- Load-based pressure from transported goods

The Proposed Model with MSP Deployment is shown in fig 4.

The integrated MSP modules sense these pressure variations. The multiple piezo layers' compress and decompress, producing electrical charges. All the generated electrical outputs are integrated into a unified energy line.

To protect the system from reverse current flow, a diode-based circuit is used. This ensures:

- Smooth power transfer to the battery
- Isolation of the battery during periods of no pressure input
- Compliance with impedance matching conditions for maximum power transfer

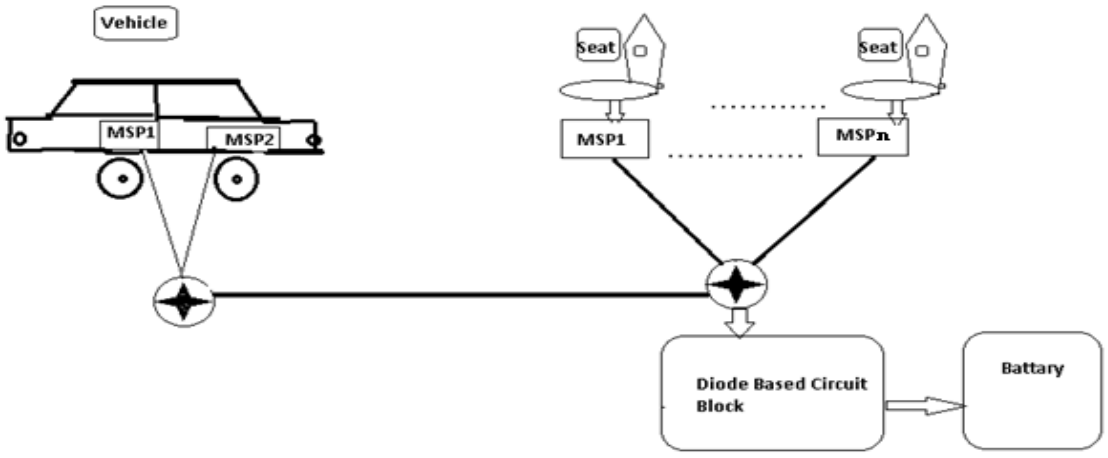


Figure 4: Proposed Model with MSP Deployment

Conclusion:

The Multi-Stranded Piezoelectric (MSP) module represents a transformative step in energy harvesting technology. By structurally reimagining how piezoelectric sensors can be arranged, protected, and interfaced with automotive systems, the MSP provides a robust, compact, and highly efficient solution for generating electrical energy from mechanical pressure.

This chapter has outlined the motivations, design principles, working mechanisms, and potential applications of the MSP system. As vehicles evolve toward greater electrification and intelligence, technologies such as MSP will play a crucial role in enhancing power availability, improving battery performance, and enabling sustainable energy utilization in real-world environments.

Future Scope:

While the current focus is on automotive systems, the MSP module can also be deployed in:

- Staircases for footstep energy harvesting
- Dance floors and entertainment venues
- Gym treadmills and fitness equipment
- Industrial machinery with vibration-prone surfaces

Future improvements in practical MSP deployment may include:

- Optimizing spring constants for different vehicle models
- Enhancing piezo material composition for higher resilience
- Integrating smart power-management ICs
- Developing modular MSP units for easy replacement and scalability

References:

1. Prabhu, R., Titare, P., Shirke, Y., & Bhavsar, S. (2023). Efficient pressure sensing using multistranded piezo MSP design for electrical energy conversion in vehicle. Patent No. 202121060523.
2. Roundy, S., Wright, P. K., & Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes. *Computer Communications, 26*(11), 1131–1144.
3. Anton, S. R., & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003–2006). *Smart Materials and Structures, 16*(3), R1–R21.
4. Zhu, D., Tudor, M. J., & Beeby, S. P. (2010). Strategies for increasing the operating frequency range of vibration energy harvesters: A review. *Measurement Science and Technology, 21*(2), 022001.

5. Kim, H. S., Kim, J. H., & Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration. *International Journal of Precision Engineering and Manufacturing, 12*(6), 1129–1141.
6. Safaei, M., Sodano, H. A., & Anton, S. R. (2019). A review of energy harvesting using piezoelectric materials: State-of-the-art a decade later (2008–2018). *Smart Materials and Structures, 28*(11), 113001.
7. Sezer, N., & Koç, M. (2021). A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. *Nano Energy, 80*, 105567.
8. Covaci, C., & Gontean, A. (2020). Piezoelectric energy harvesting solutions: A review. *Sensors, 20*(12), 3512.
9. Xie, X. D., & Wang, Q. (2015). Energy harvesting from a vehicle suspension system. *Energy, 86*, 385–392.
10. Abdelkareem, M. A., Xu, L., Ali, M. K. A., Elagouz, A., Mi, J., Guo, S., … & Zuo, L. (2018). Vibration energy harvesting in automotive suspension system: A detailed review. *Applied Energy, 229*, 672–699.
11. Bowen, C. R., Kim, H. A., Weaver, P. M., & Dunn, S. (2014). Piezoelectric and ferroelectric materials and structures for energy harvesting applications. *Energy & Environmental Science, 7*(1), 25–44.
12. Elahi, H., Eugeni, M., & Gaudenzi, P. (2018). A review on mechanisms for piezoelectric-based energy harvesters. *Energies, 11*(7), 1850.

A STATISTICAL STUDY OF CLIMATE CHANGE IN NASHIK DISTRICT

Nutan V. Khangar* and Kalpesh P. Amrutkar

Department of Statistics,

K.R.T. Arts, B.H. Commerce and A.M. Science (KTHM) College, Nashik, India

*Corresponding author E-mail: nutankhangar@kthmcollege.ac.in

Abstract:

Climate change poses increasing risks to agriculture, particularly in regions dependent on climate-sensitive crops. This study analyses long-term climatic behaviour in Nashik District using NASA POWER meteorological data from 1987–2020. Simple Correspondence Analysis (SCA) is employed to examine the associations among key climate variables, including temperature, precipitation, humidity, and windspeed. The analysis reveals strong interrelationships among these variables, along with clear seasonal clustering that highlights systematic patterns in temperature and rainfall across months. These findings provide a deeper understanding of local climate dynamics and underscore the importance of statistical approaches in climate-risk assessment, agricultural planning, and the development of weather-based crop insurance schemes.

Keywords: Climate Change, Correspondence Analysis, Temperature Modelling.

1. Introduction:

Climate change refers to long-term shifts in global or regional climatic patterns, typically observed over decades or longer periods. This phenomenon encompasses variations in temperature, rainfall, and extreme weather occurrences that significantly influence natural ecosystems and human activities. Climate plays a decisive role in shaping environmental processes, water resource availability, and agricultural productivity. Over the past decade, substantial scientific attention has focused on understanding historical climate change at global and regional levels, driven by its critical implications for socio-economic development and food security. Agriculture, being inherently climate-dependent, is one of the most vulnerable sectors. In India, climate impacts are particularly severe because a large share of agricultural land is rain-fed and highly sensitive to fluctuations in temperature, precipitation, and extreme weather conditions. Farmers frequently face partial or complete crop failures caused by controllable risks, such as pests and plant diseases, and uncontrollable risks, such as droughts, heatwaves, unseasonal rainfall, and climatic extremes. Crop selection in Indian agriculture is guided largely by regional climatic suitability, and any imbalance—such as unexpected increases in temperature

or heavy rainfall during flowering or harvesting—can drastically disturb productivity. Understanding how climate is changing is therefore essential for resilient agricultural planning, adaptation strategies, and long-term policy development. Weather-based crop insurance has emerged as an important tool to mitigate agricultural risk and provide compensation against climate-induced losses.

Nashik is one of India's most prominent agricultural and horticultural districts, especially recognized for grape cultivation. Popularly known as the "grape capital of India," Nashik has long-established agricultural expertise supported by favourable climatic conditions and advanced cultivation practices. As of December 2015, Nashik had approximately 1.75 lakh hectares under grape cultivation and produced about 10 lakh metric tonnes of grapes annually, with an average yield of nearly 20 metric tonnes per hectare. The district accounts for nearly 55% of India's total grape exports and around 75% of Maharashtra's share. Export figures demonstrate substantial growth: from roughly 4,000 metric tonnes in 2003 to more than 48,000 metric tonnes in 2013, and over 65,000 metric tonnes in 2014. Key grape-growing regions include Kalvan, Peint, Igatpuri, Sinnar, Niphad, Yeola, Nandgaon, Satana, Surgana, Dindori, and Malegaon. Major export destinations include Netherlands, Germany, Belgium, and the United Kingdom, while Russia and China have recently emerged as significant markets. Such high levels of dependence on grape cultivation mean that even moderate climatic variations could have serious economic consequences for farmers and regional trade.

Grapes require a specific climatic environment for optimal growth. They are ideally cultivated in areas with hot and dry conditions, requiring temperatures between 15°C and 40°C. Extreme temperatures above 40°C during the fruit development stage reduce fruit set and decrease berry size, while temperatures below 15°C following forward pruning impair bud break, potentially leading to crop failure. Adequate sunlight is crucial for fruitfulness, with light intensity of around 2,400 ft-candles considered ideal. Low light conditions during the active growth stage (45–75 days after pruning) negatively affect bud development. Ideal elevations range from 200–250 meters above mean sea level. Areas with annual rainfall not exceeding 900 mm and evenly distributed throughout the year are most suitable; however, rainfall during flowering or ripening causes downy mildew and other fungal infections. Excessive atmospheric humidity increases vegetative growth and deteriorates fruit quality. Thus, the success of grape cultivation depends heavily on stable and predictable climatic conditions.

Climate variability and long-term climate change have become central issues in both global and Indian agricultural research. Successive IPCC reports highlight rising temperatures, altered precipitation distribution, increasing frequency of droughts and storms, and intensification of

extreme events as major challenges for food security. In India, long-term climate analyses (Dash *et al.,* 2007; Singh & Sontakke, 2002) reveal increasing variability in rainfall patterns, while subsequent studies (Kothawale & Rupa Kumar, 2005; Pai *et al.,* 2020) document upward trends in minimum temperatures and warmer nights. Regional analyses in Maharashtra indicate strong linkages between temperature increases, rainfall decline, and agricultural yield loss, particularly in semi-arid zones (Naidu *et al.,* 2017; Patil *et al.,* 2021). This evolving climate behaviour emphasizes the need for sophisticated analytical tools to quantify climatic associations and risk patterns.

In this context, Correspondence Analysis (CA) has emerged as a powerful multivariate method capable of identifying complex relationships in large climate datasets. CA has gained increasing recognition in environmental and climate research for its effectiveness in analysing associations between categorical variables. Greenacre (2007) established its theoretical foundation, and subsequent research demonstrated its applicability in studying seasonality, rainfall patterns, and climatic cluster transitions (Beh & Lombardo, 2014; Cembalo *et al.,* 2021; Lima *et al.,* 2022). Alongside multivariate methods, stochastic modelling approaches particularly Markov chains—are widely used to examine persistence, transition behaviour, and probability structures of climate variables. Wilks (2011) and Ailliot *et al.,* (2015) significantly advanced In agricultural insurance research, Markov-based indices enable transparent risk estimation and premium calculation (Chavan & Shinde, 2018; Ramasubramanian *et al.,* 2020), supporting science-based crop insurance policy development.

The present study contributes to this expanding literature by applying CA to 34 years of climatic data from Nashik District. The study investigates associations among climatic variables, examines seasonal patterns, develops transition probability matrices for temperature-based stochastic processes, analyses probabilistic characteristics of climatic distributions, and derives joint distributions of runs in Bernoulli sequences to understand clustering of extreme climatic events. These insights are expected to support climate risk assessment and enhance weather-indexed crop insurance models to protect farmers against increasing climatic uncertainty.

2. Methodology:

Simple Correspondence Analysis (SCA)

CA is a multivariate statistical technique used to graphically represent and interpret associations among categorical variables in a contingency table. It enables dimensionality reduction while preserving the essential structure of the data, thereby providing an intuitive visual display of relationships between categories. In the present study, CA is employed to examine associations among selected climate variables. Since climatic parameters such as temperature, precipitation,

humidity, and windspeed are continuous in nature, they were first converted into categorical variables by constructing meaningful class intervals based on climatological ranges and distribution characteristics. These categorized variables were then used to construct an $I \times J$ contingency table N, where I and J denote the number of categorical levels of the two selected correspondence variables.

SCA was subsequently applied to the contingency table to explore the underlying structure of associations. The method decomposes the chi-square distance between row and column profiles into principal dimensions, which are represented graphically using bi-plots. Categories positioned close to one another on the plot indicate similar climatic behaviour, while distant points reflect contrasting patterns. This graphical interpretation provides insight into seasonal clustering and co-movement among climatic variables, offering a powerful tool for understanding climate variability and supporting climate-responsive agricultural decision-making.

Case Study

For this study data is obtained from "The Power Project" which provide solar and meteorological data sets from NASA Research for support of renewable energy, building energy efficiency and agriculture needs. The 'Power Single Point data Access' provides access to datasets by single point by its Latitude & Longitude.

The following variables are considered for the study.

- QV2M: Specific Humidity at 2 Meters (g/kg)
- T2M: Temperature at 2 Meters (C)
- T2M_MAX: Maximum Temperature at 2 Meters (C)
- T2M_MIN: Minimum Temperature at 2 Meters (C)
- WS10M: Wind Speed at 10 Meters (m/s)
- WS10M_MAX: Maximum Wind Speed at 10 Meters (m/s)
- WS10M_MIN: Minimum Wind Speed at 10 Meters (m/s)
- WS50M: Wind Speed at 50 Meters (m/s)
- WS50M_MAX: Maximum Wind Speed at 50 Meters (m/s)
- WS50M_MIN: Minimum Wind Speed at 50 Meters (m/s)
- PRECTOT: Precipitation (mm day-1)
- RH2M: Relative Humidity at 2 Meters (%)

3. Presentation Data

We visualize our data using simple bar plot for each variable under consideration. From Figure 1 we observed that, the yearly precipitation exhibits considerable variability, characterized by alternating phases of increase and decrease over the study period. We observed changes in Temperature (Figure 2) as well. When the precipitation was minimum the temperature was high. There might be some association between precipitation and temperature. We have analyzed the association between them using correspondence analysis.

From Figure 4 And Figure 5, we observed not much difference between the minimum temperature and maximum temperature. We also visualize Specific Humidity (Figure5) and relative humidity (Figure 6), windspeed at different level (10 meters and 50 meters from the surface of earth, (Figure 7 and Figure 10) and minimum and maximum wind speed (Figure 8, 9, 11 and 12).

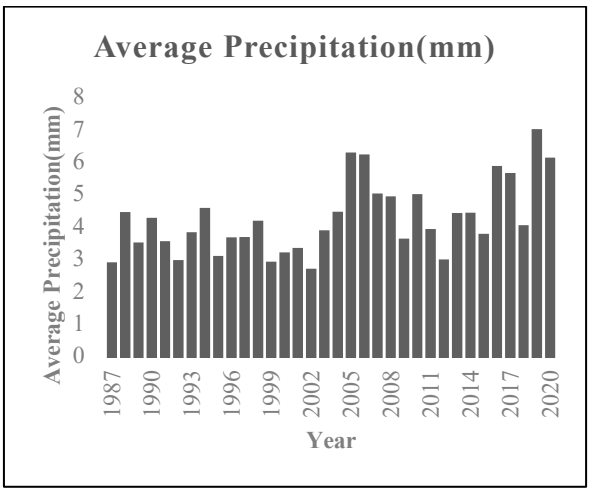


Figure 1: Yearly Average Precipitation (mm)

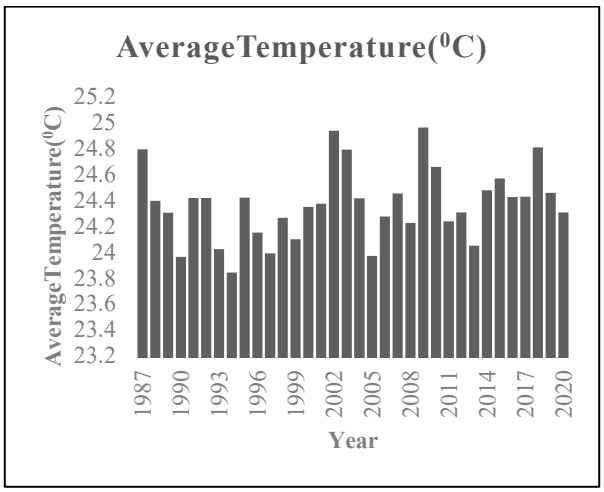


Figure 2: Yearly Average Temperature (^{0}C)

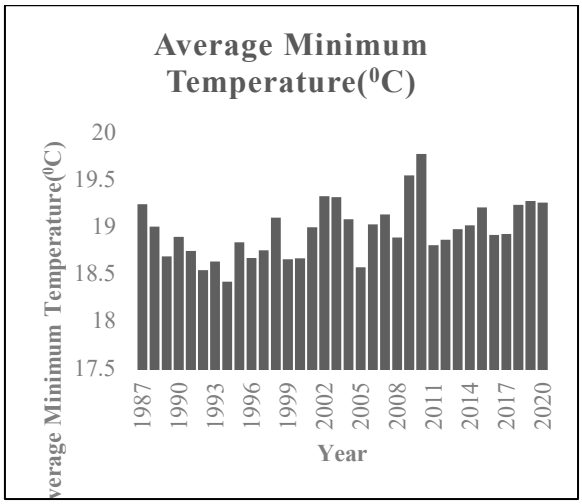


Figure 3: Yearly Average Minimum Temperature (^{0}C)

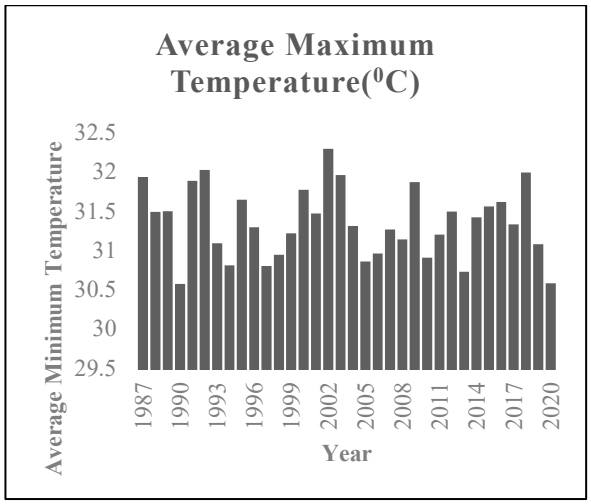


Figure 4: Yearly Average Maximum Temperature (^{0}C)

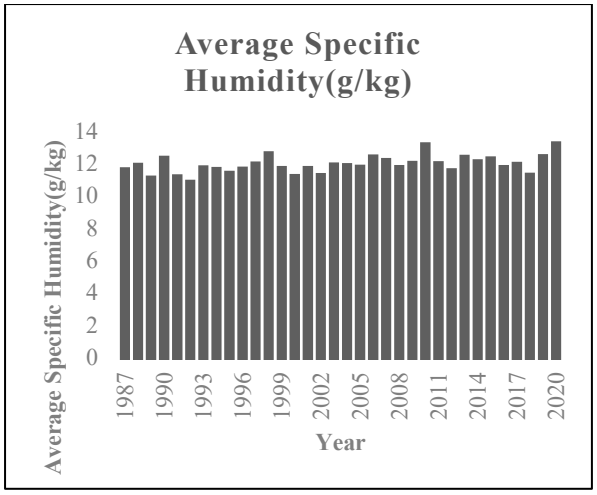


Figure 5: Average Specific Humidity (g /kg)

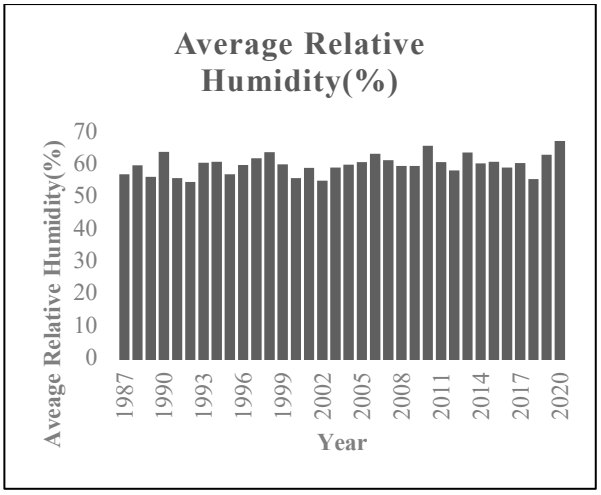


Figure 6: Yearly Average Relative Humidity

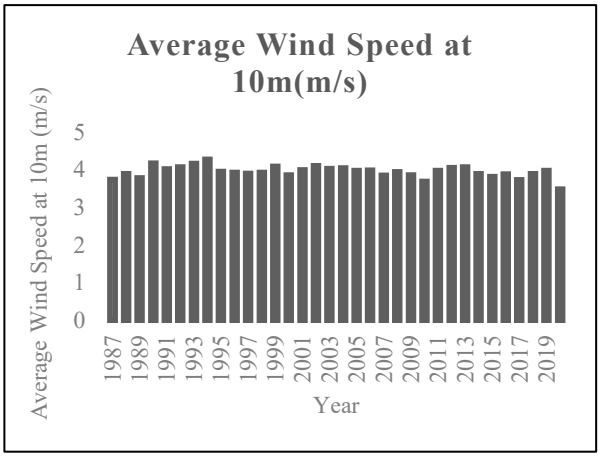


Figure 7: Yearly Average Wind Speed at 10 meters (m/s)

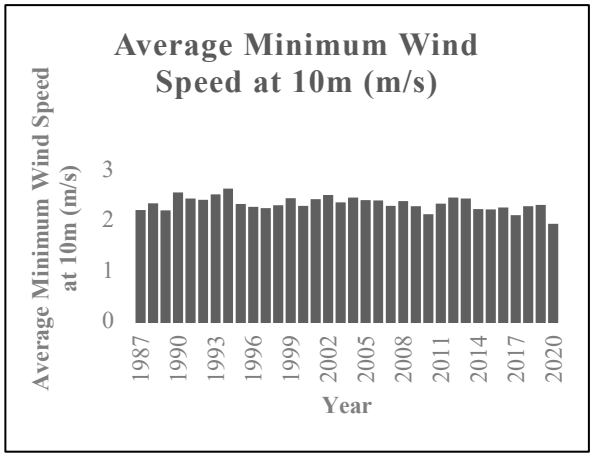


Figure 8: Yearly Average Minimum Wind Speed at 10 meters (m/s)

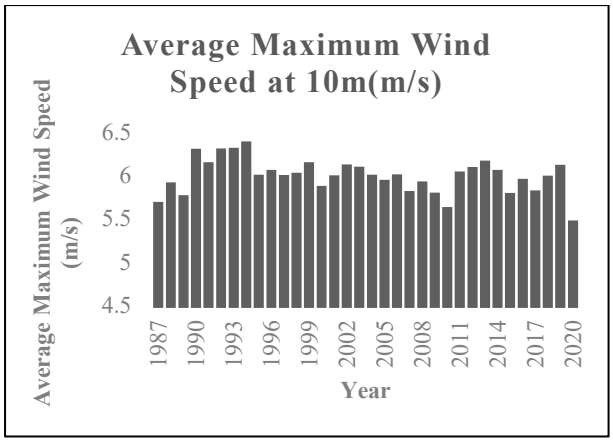


Figure 9: Yearly Average Maximum Wind Speed at 10 meters (m/s)

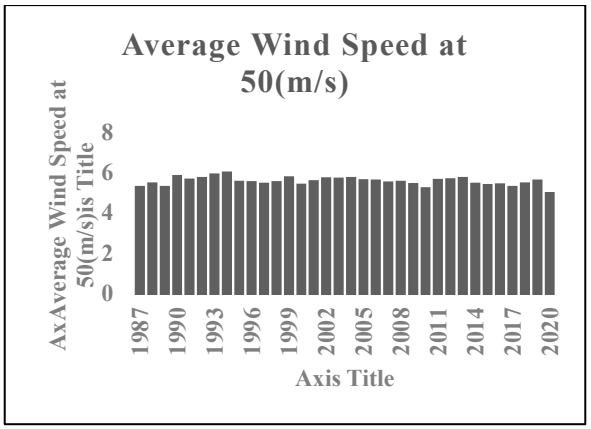


Figure 10: Yearly Average Wind Speed at 50 meters (m/s)

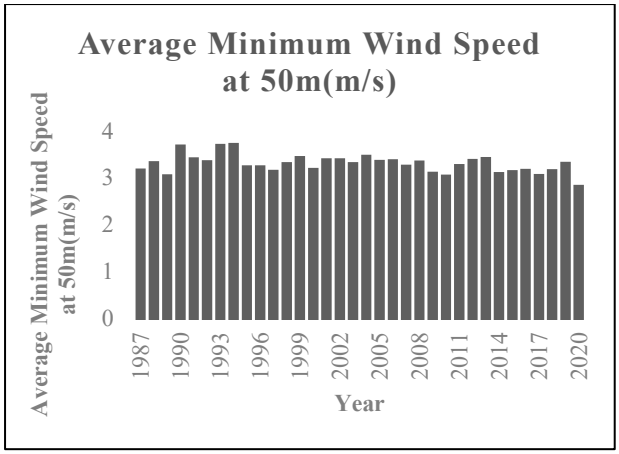


Figure 11: Yearly Average Minimum Wind Speed at 50 meters (m/s)

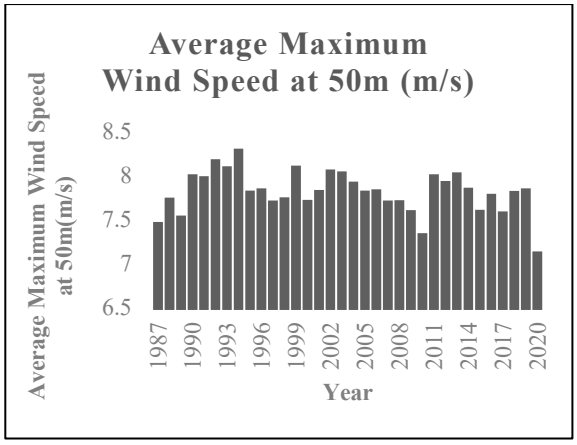


Figure 12: Yearly Average Maximum Wind Speed at 50 meters (m/s)

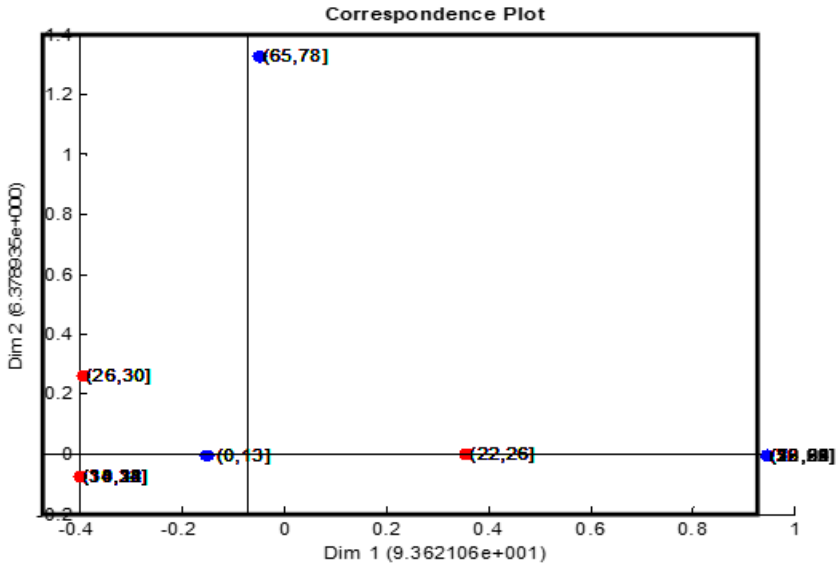


Figure 13: Association Between Temperature and Precipitation

Summary Statistics

Statistic	**Precipitation**	**Temperature**	**Minimum Temperature**	**Maximum Temperature**	**Specific Humidity**	**Relative Humidity**
	PRECTOT	***T2M***	***T2M_MIN***	***T2M_MAX***	***QV2M***	***RH2M***
Mean	4.15515	24.3484	18.93647	31.31461	11.86255	58.81309
Standard Error	0.09986	0.029093	0.034079	0.04115	0.046112	0.230262
Median	0	23.88	20.13	29.97	11.86	57.42
Mode	0	23.55	21.67	27.93	17.6	89.31
Standard Deviation	11.1285	3.242193	3.797821	4.585799	5.138754	25.66052
Minimum	0	13.51	5.7	21.48	0.99	5.69
Maximum	160.93	34.84	27.17	43.97	20.64	96.6
Sum	51602.81	302382.8	235172	388896.2	147321	730399.8

Statistic	**Wind Speed**	**Wind Speed**	**Minimum Wind Speed**	**Maximum Wind Speed**	**Minimum Wind Speed**	**Maximum Wind Speed**
	WS10M	***WS50M***	***WS10M_MIN***	***WS10M_MAX***	***WS50M_MIN***	***WS50M_MAX***
Mean	3.95	5.4539	2.2597	5.9675	3.2574	7.78741
Standard Error	0.0152	0.0180	0.0145	0.017998	0.02092	0.01827
Median	3.47	5.01	1.89	5.77	2.75	7.72
Mode	3.01	4.36	1.83	6.19	0.69	8.02
Standard Deviation	1.69136	2.0089	1.6139	2.0057	2.3310	2.03607
Range	12.9	16.47	9.99	15.8	13.15	19.81
Minimum	0.81	1	0.01	1.33	0.01	1.95
Maximum	13.71	17.47	10	17.13	13.16	21.76
Sum	48998.95	67732.33	28062.73	74109.86	40454.24	96711.85

Numerical Result obtained by Simple CA

SCA was performed on contingency table cross-classified within the variable's temperature and precipitation for year 2020 which is given in Table 1 and the numerical analysis given in Table 2.

Table 1: Contingency table of correspondence variables temperature and precipitation for year 2020

Temperature	**Precipitation**						
	(0,13]	**(13,26]**	**(26,39]**	**(39,52)**	**(52,65]**	**(65,78]**	**(78,91]**
(14,18]	18	0	0	0	0	0	0
(18,22]	74	0	0	0	0	0	0
(22,26]	142	25	13	7	3	1	2
(26,30]	39	0	0	0	0	1	0
(30,34]	41	0	0	0	0	0	0

Table 2: Result of SCA

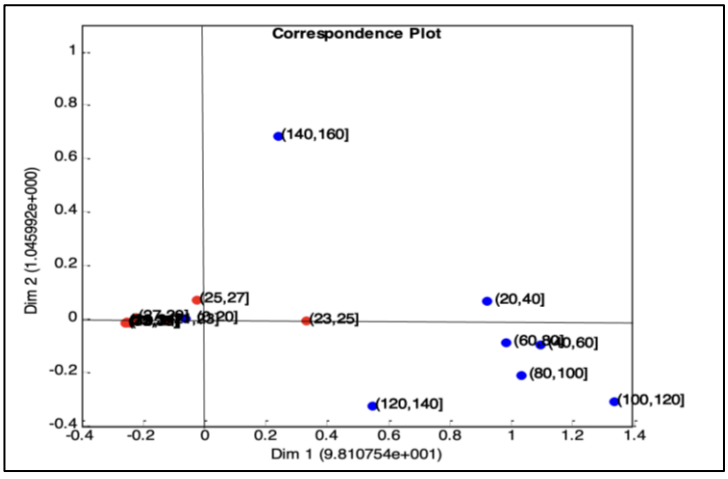
Singular Values	**Inertia**	**Chi-square**	**Percentage**
0.3767	0.1419	51.9297	93.6211
0.0983	0.0097	3.5383	6.3789
Total	0.1516	55.468	100
Chi-square	55.4856	-	-
d. f.	24	-	-
p-value	2.6915e-004	-	-

Observe that, the two axes explain almost 100% of the total inertia. The principal inertia along the two principal axes is 0.1516. Thus, it is a remarkably good plot for representing the variation of row and column profiles. The association between temperature and precipitation Figure 13. can be interpreted as follows.

When precipitation is less than $13mm$ then temperature would lie between $26\ to\ 34$ ℃. Temperature and precipitation are associated. Similarly, we have Contingency table of correspondence variables temperature and precipitation for year 1987 to 2020 and SCA was performed on it. The resulting table is given in Table 3.

Table 3: Result of SCA

Singular Value	Inertia	Chi-square	% of Inertia
0.2491	0.062	770.4937	98.1075
0.0257	0.0007	8.2148	1.046
0.0228	0.0005	6.4314	0.8189
0.0041	0	0.208	0.0265
0.0008	0	0.0084	0.0011
Total	0.0632	784.8808	100
Chi-squared statistic	784.8808	-	-
DF	70	-	-
p-value	0	-	-



Contingency table of correspondence variables temperature and months of the year 1987 and 2020 was formed and performing SCA on it, the numerical result obtained is given in Table 4 and Table 5. Similarly, contingency table was formed for other two variables and their numerical results given in Table 6 and Table 7.

Table 4: Result of SCA

Singular value	Inertia	Chi-square	Percentage
0.9186	0.8438	308.8219	47.1806
0.7922	0.6277	229.7218	35.096
0.4299	0.1848	67.6361	10.3332
0.3635	0.1322	48.3733	7.3903
Total	1.7885	654.5531	100
Chi-square	654.591	-	-
DF	44	-	-
p-value	0	-	-

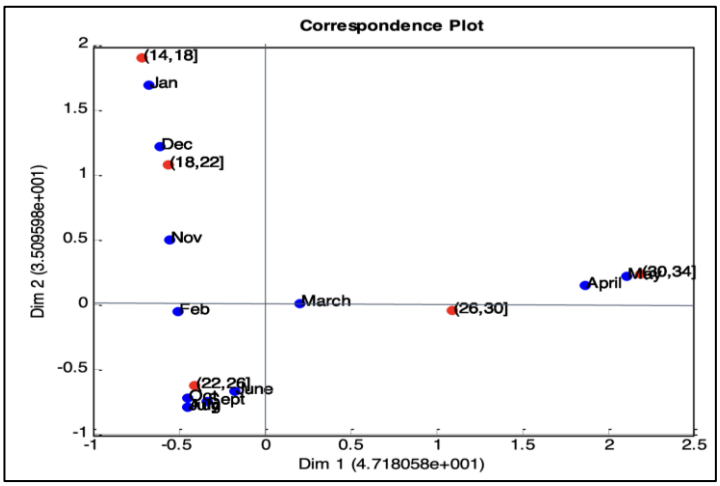


Table 5. Result of SCA

Singular Value	Inertia	Chi-square	Percentage
0.8832	0.7801	9.526	52.567
0.6938	0.4813	5.8779	32.4357
0.4008	0.1606	1.9615	10.8241
0.199	0.0396	0.4838	2.6698
0.0932	0.0087	0.1062	0.5858
0.0841	0.0071	0.0864	0.4765
0.0672	0.0045	0.0551	0.3041
0.0447	0.002	0.0244	0.1346
0.0058	0	0.0004	0.0023
0.0013	0	0	0.0001
Total	1.4839	18121.7	100
Chi-square	18428.55	-	-
d. f.	110	-	-
p-value	0	-	-

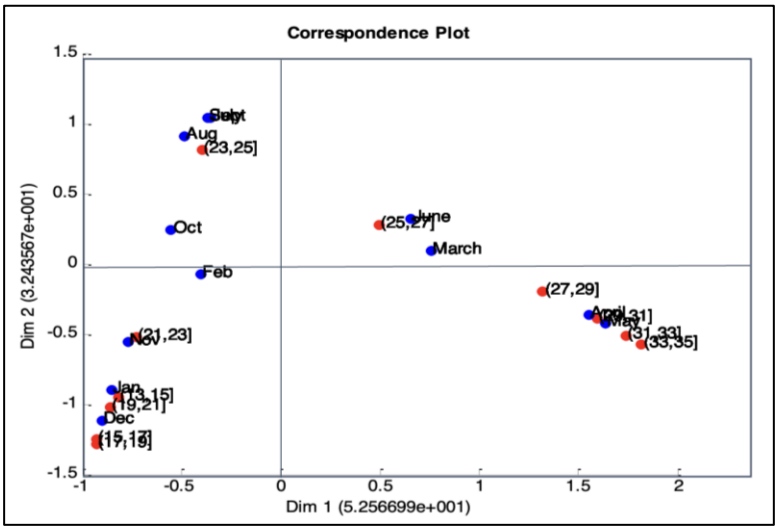


Table 6: Result of SCA

Singular Value	Inertia	Chi-square	Percentage
0.8596	0.7389	9.1767	76.5587
0.452	0.2043	2.5374	21.1692
0.1287	0.0166	0.2058	1.7166
0.0732	0.0054	0.0666	0.5554
Total	0.9652	11986.5	99.9999
Chi-square	11986.82	-	-
d. f.	44	-	-
p-value	0	-	-

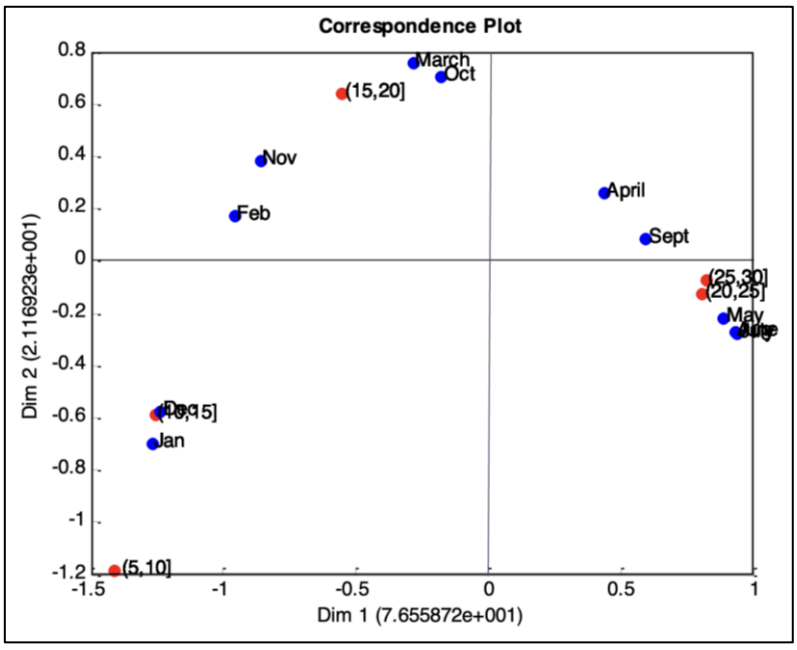
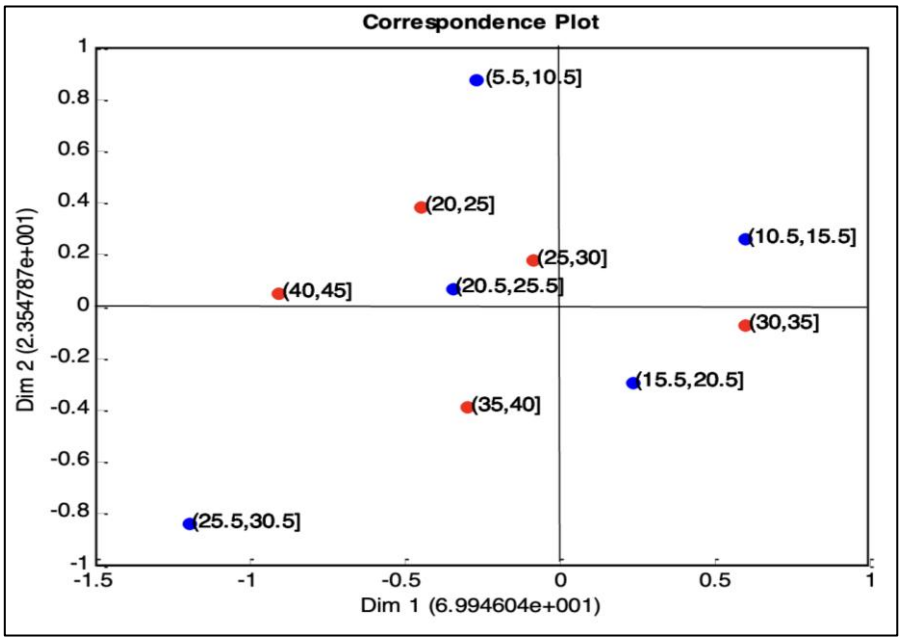


Table 7: Result of SCA

Singular Value	Inertia	Chi-square	Percentage
0.3893	0.1516	1.8825	69.946
0.2259	0.051	0.6338	23.5479
0.111	0.0123	0.1531	5.6884
0.0421	0.0018	0.022	0.8177
Total	0.2167	2691.4	100
Chi-Sq	2632.688	-	-
d.f.	16	-	-
p-value	0	-	-



Conclusion:

The analysis of long-term climate data for Nashik District reveals important associations among key climatic variables. From the barplots of yearly average temperature and precipitation, it is evident that years with lower precipitation generally correspond to higher temperatures. Although average temperatures exhibit fluctuations without a clear long-term trend, precipitation shows a noticeable increase after 2005 compared with earlier years, with 2019 recording the highest level during the study period.

CA provides deeper insight into these relationships. The association between temperature and precipitation in 2020 indicates that when precipitation falls below 13 mm, temperatures predominantly lie between 26°C and 34°C, reinforcing the inverse relationship between the two variables. Extending this assessment across the entire 33-year period (1987–2020) further

confirms the consistent pattern that lower precipitation is associated with higher temperature levels.

Similarly, the correspondence analysis of temperature and month highlights strong seasonal dependence, demonstrating that temperature patterns vary systematically throughout the year. The examination of minimum and maximum temperatures also reveals close alignment, with relatively small differences observed across the study period.

Overall, establishing these associations among temperature, precipitation, and seasonal variability enhances our understanding of climate behaviour in Nashik District. Such insights are essential for interpreting long-term climate change trends and understanding their broader implications for agricultural activities and planning.

Acknowledgement:

The first author would like to thak Savitribai Phule Pune University, Pune for providing the research fund under ASPIRE scheme with reference number 21TEC000231.

References:

1. Aggarwal, P. K., Hebbar, K. B., Venugopalan, M. V., Rani, S., Bala, A., Biswal, A., & Wani, S. P. (2019). Climate change and India's food security: Impacts, vulnerability and adaptation options. *Journal of Agrometeorology, 21*(1), 1–10.
2. Ailliot, P., Allard, D., Monbet, V., & Naveau, P. (2015). Stochastic weather generators: An overview of weather type models. *Journal de la Société Française de Statistique, 156*, 101–113.
3. Allan, R. P., Soden, B. J., John, V. O., Ingram, W., & Good, P. (2014). Current changes in tropical precipitation. *Environmental Research Letters, 9*(10), 1–14.
4. Basha, G., Kishore Kumar, K., & Venkat Ratnam, M. (2022). Increasing trends in extreme weather events over India. *Climate Dynamics, 58*, 1427–1446.
5. Beh, E. J., & Lombardo, R. (2014). Correspondence analysis: Theory, practice and new strategies. Chichester: Wiley.
6. Chattopadhyay, S., & Ghosh, S. (2022). Assessing long-term climate variability using machine learning and statistical models. *Climate Research, 87*, 153–170.
7. Chavan, R. N., & Shinde, R. L. (2018). Markov chain modeling of stochastic process defined on daily minimum temperature and its application in weather-based crop insurance scheme for banana. *Mausam, 69*(1), 156–160.
8. Cembalo, A., Caracciolo, F., Lombardi, A., & Lombardo, R. (2021). Assessment of climate change in Italy by variants of ordered correspondence analysis. *Stats, 4*, 146–161.

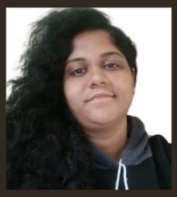
9. Dash, S. K., Jenamani, R. K., Kalsi, S. R., & Panda, S. K. (2007). Some evidence of climate change in twentieth-century India. *Climatic Change, 85*, 299–321.
10. Dubey, R., Mishra, V. N., & Singh, A. (2021). Temperature and rainfall extremes for agricultural risk management in Western India. *Theoretical and Applied Climatology, 145*, 1297–1311.
11. Ghosh, S., & Mujumdar, P. P. (2007). Nonparametric methods for modeling rainfall–runoff relationships. *Advances in Water Resources, 30*, 1325–1333.
12. Greenacre, M. (2007). Correspondence analysis in practice (2nd ed.). Chapman & Hall/CRC.
13. IPCC. (2014). Climate Change 2014: Impacts, adaptation, and vulnerability. Cambridge University Press.
14. IPCC. (2021). Climate Change 2021: The physical science basis. Cambridge University Press.
15. Kothawale, D. R., & Rupa Kumar, K. (2005). On the recent changes in surface temperature trends over India. *Geophysical Research Letters, 32*(18), 1–4.
16. Kumar, A., & Chandrasekaran, S. (2023). Probabilistic modelling for climate-risk insurance in horticulture. *Agricultural Finance Review, 83*(2), 234–249.
17. Laipelt, L., Souza, V., & dos Santos, S. (2022). Assessment of NASA POWER reanalysis data for agricultural applications. *Agricultural Water Management, 263*, 107512.
18. Lima, M. R., Pires, C. F., & da Silva, W. (2022). Using correspondence analysis to identify climatic patterns in agricultural zones. *Environmental Modelling & Software, 152*, 105393.
19. Mahul, O., & Stutley, C. J. (2020). Government support to agricultural insurance: Challenges and options for developing countries. World Bank Publications.
20. Mall, R. K., Singh, R., Gupta, A., Srinivasan, G., & Rathore, L. S. (2006). Impact of climate change on Indian agriculture: A review. *Climatic Change, 78*, 445–478.
21. Naidu, D., Raghuwanshi, N. S., & Mishra, A. (2017). Trend analysis of climate variables in Maharashtra. *Journal of Water and Climate Change, 8*(2), 241–255.
22. Narayanan, S., Raju, S. S., & Kumar, P. (2022). Weather index insurance in India: Performance, gaps and opportunities. *Climate Risk Management, 36*, 100443.
23. Pai, D. S., Sridhar, L., Rajeevan, M., & Sreejith, O. P. (2020). Long-term climate assessment over India. *Mausam, 71*(2), 317–340.
24. Patil, J. A., Thorat, T. M., & Jadhav, A. (2021). Rainfall and temperature variability in semi-arid Maharashtra. *Journal of Agrometeorology, 23*(2), 181–188.

25. Praveen, B., Talukdar, S., & Shashidhar, K. S. (2021). Machine-learning approaches for climate trend detection in India. *Arabian Journal of Geosciences, 14*, 1–17.
26. Rajeevan, M., Gadgil, S., & Bhate, J. (2012). Active and break spells of the Indian summer monsoon. *Journal of Earth System Science, 121*(3), 599–620.
27. Singh, D., & Sontakke, N. A. (2002). On climatic fluctuations and environmental changes of India. *Climate Research, 22*, 69–78.
28. Singh, P., Dutta, D., & Tripathi, A. (2023). Rainfall seasonality analysis using correspondence analysis. *Natural Hazards, 121*, 1883–1901.
29. Srivastava, A. K., Das, M. K., & Gupta, V. (2021). Temperature and rainfall extremes over India: Recent trends. *Journal of Climate, 34*, 405–423.
30. Stackhouse, P. W., *et al.,* (2018). NASA POWER: A solar and meteorological data resource for climate-impact studies. *Earth and Space Science, 5*, 532–547.
31. Trenberth, K. E., & Shea, D. J. (2005). Relationships between precipitation and surface temperature. *Geophysical Research Letters, 32*(14), 1–4.
32. Wilks, D. S. (2011). Statistical methods in the atmospheric sciences (3rd ed.). Academic Press.

Environmental Sustainability: Emerging Perspectives and Practices Volume II
(ISBN: 978-93-48620-51-4)

About Editors

Dr. K. Maruliya Begam is an accomplished academician, researcher, and engineering professional with over 14 years of experience in Electrical and Electronics Engineering. She holds a Ph.D. in Electrical Engineering from Anna University, specializing in hybrid machine-learning neural network models for multi-step wind speed forecasting. Her expertise extends to battery technologies, electric vehicles, renewable energy systems, distributed generation, control systems, and power system engineering. She has served in key academic and administrative roles, including Associate Professor and Head of the EEE Department at Periyar Maniammai Institute of Science & Technology, Head of the EEE Department at Arulmurugan College of Engineering, and Assistant Professor at M. Kumarasamy College of Engineering. She has contributed to NAAC coordination, innovation and incubation, entrepreneurship development, accreditation processes, and student mentoring. With numerous Scopus and Web of Science publications, IEEE papers, and patents from the UK and India, she has made impactful research contributions in energy systems and smart grid technologies. She has guided many student projects, delivered expert lectures, and served as coordinator and jury member for major state-level hackathons. Recognized with honours such as the Dr. APJ Kalam Trust Young Women Scientist Award and the Rising Star Award, she continues to promote sustainable energy research, academic excellence, and technological innovation.



K. Safana Yasmin is a dedicated academic professional serving as an Assistant Professor in the Department of Computer Science and Engineering at V.S.B. Engineering College, Karur. She holds an M.E. in Computer Science and Engineering from Arulmurugan College of Engineering with an excellent academic record, along with a B.Tech in Information Technology from Chettinad College of Engineering and Technology. She has previously worked as a Lecturer and Aptitude & Personality Development Trainer in reputed engineering institutions, significantly contributing to student development and academic excellence. Her teaching expertise includes Software Engineering, Computer Networks, and Operating Systems. She possesses strong technical skills in C, C++, SQL, ERP systems, and Oracle-based report development. Known for her leadership qualities, effective communication, and exceptional organizational abilities, she is committed to delivering quality education and mentoring students through a student-centered approach. She actively engages in continuous professional development, striving to enhance her teaching and technical competencies. Passionate, sincere, and adaptable, she contributes meaningfully to institutional growth while fostering a supportive learning environment that motivates students toward academic and professional success.

Bhumi Publishing

ISBN 978-93-48620-51-4
9 789348 620514