

ISBN: 978-81-69967-17-4

ENVIRONMENTAL CHALLENGES AND HUMAN HEALTH

INTEGRATING SCIENCE FOR A SUSTAINABLE FUTURE

Editors

Dr. Palukurty Mary Anupama

Dr. Mousami Shankar Addala

First Edition: October 2026



BHUMI PUBLISHING



ST. JOSEPH'S COLLEGE FOR WOMEN (AUTONOMOUS) VISAKHAPATNAM

EXCELLENCE | EMPOWERMENT | SERVICE



ABOUT THE COLLEGE

St. Joseph's College for Women (Autonomous), Visakhapatnam, was established in 1958 by the Sisters of St. Joseph of Annecy. Affiliated to Andhra University and granted autonomous status in 1987, the College has grown into a distinguished centre of higher education dedicated to the empowerment and holistic development of young women.

With the motto "Quality and Excellence: Hallmark of St. Joseph's," the institution nurtures intellectual curiosity, leadership, confidence, social responsibility and global competencies. The College offers a wide range of undergraduate and postgraduate programmes across Arts, Science, Commerce, Management and Home Science, along with skill-oriented, certificate and diploma courses, in accordance with UGC and APSICHE guidelines.



Nurturing Women, Building a Brighter Tomorrow



Holistic Education



Empowered Women



Leadership and Innovation



Social Responsibility



Global Competencies

DEPARTMENT OF BIOCHEMISTRY

Established in 2008, the Department of Biochemistry at St. Joseph's College for Women (Autonomous), Visakhapatnam, is a vibrant centre for undergraduate education, practical learning and scientific enrichment.

The department offers a B.Sc. (Biochemistry) programme, providing students with a strong foundation in biochemistry and allied life sciences through classroom teaching, laboratory training, project work and experiential learning.

The department is supported by dedicated faculty members, Dr. P. Mary Anupama and Dr. Mousami Shanker Addala, who contribute to teaching, student mentoring, academic development, research guidance and the enrichment of departmental activities.

The department regularly organizes seminars, webinars, conferences, workshops, guest lectures, hands-on training programmes, research projects, competitions and outreach activities to foster scientific curiosity, critical thinking, communication skills and social responsibility.



**EXPLORE
&
INNOVATE**

*Understanding Life
for a Healthier
Tomorrow*

ABOUT THE CONFERENCE

The International Conference on Recent Advances in Biological Sciences, scheduled for 10th–11th September 2026 at St. Joseph's College for Women (A), Visakhapatnam, focuses on "Environmental Challenges and Human Health: Integrating Science for a Sustainable Future."

The conference is especially relevant in the present scenario, as climate change, pollution, biodiversity loss, food insecurity and emerging health challenges are increasingly interconnected, demanding interdisciplinary scientific solutions. The conference invites researchers, academicians, scientists, students and professionals to present their latest research through paper presentations and poster presentations, both online and offline.

CONFERENCE THEMES

- 1 Environmental Sustainability, Climate Change and Public Health
- 2 Plant Metabolomics, Natural Products and Therapeutic Innovations
- 3 Food, Nutrition and Sustainable Living
- 4 Emerging Trends in Healthcare and Precision Medicine
- 5 Artificial Intelligence, Omics Technologies and Data-Driven Health Research

The conference aims to create a platform for knowledge sharing, collaboration and innovative ideas towards a healthier planet and a sustainable future.



**Integrating Science
for a Sustainable Future**

Environmental Challenges and Human Health:

Integrating Science for a Sustainable Future

(ISBN: 978-81-69967-17-4)

DOI: <https://doi.org/10.5281/zenodo.23523950>

Editors

Dr. Palukurty Mary Anupama

Convener and Head, Department of Biochemistry
St. Joseph's College for Women (A), Visakhapatnam

Dr. Mousami Shankar Addala

Co-Convener and Assistant Professor, Department of Biochemistry
St. Joseph's College for Women (A), Visakhapatnam



October 2026

Copyright © Editors

Title: Environmental Challenges and Human Health:

Integrating Science for a Sustainable Future

Editors: Dr. Palukurty Mary Anupama and Dr. Mousami Shankar Addala

First Edition: October 2026

ISBN: 978-81-69967-17-4



DOI: <https://doi.org/10.5281/zenodo.23523950>

All rights reserved. No part of this publication may be reproduced or transmitted, in any form or by any means, without permission. Any person who does any unauthorized act in relation to this publication may be liable to criminal prosecution and civil claims for damages.

Published by Bhumi Publishing,

a publishing unit of Bhumi Gramin Vikas Sanstha



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

The rapid advancement of biological sciences has created new opportunities to address contemporary challenges concerning environmental sustainability, human health, nutrition, and scientific innovation. Recognizing the importance of interdisciplinary research, the Department of Biochemistry, in collaboration with the Internal Quality Assurance Cell (IQAC), St. Joseph's College for Women (Autonomous), Visakhapatnam, organized the International Conference on Recent Advances in Biological Sciences on 10th and 11th September 2026.

The primary aim of this conference was to provide a platform for academicians, researchers, healthcare professionals, research scholars, and students to exchange scientific knowledge, present research findings, and explore innovative approaches to emerging challenges. The deliberations focused on five subthemes: environmental sustainability, climate change and public health; plant metabolomics, natural products and therapeutic innovations; food, nutrition and sustainable living; emerging trends in healthcare and precision medicine; and artificial intelligence, omics technologies and data-driven health research.

This book comprises 17 chapters contributed by authors representing diverse perspectives in biological sciences. The contributions seek to enrich scientific understanding, encourage interdisciplinary collaboration, and highlight the relevance of contemporary research to human well-being and a sustainable future.

We express our sincere gratitude to the management of St. Joseph's College for Women (Autonomous), particularly Dr. Sr. Shyji P.D., Principal and Correspondent, for her constant encouragement and institutional support. We gratefully acknowledge the advisory committee members: Sr. Hema, Sr. K.C. Mary, Dr. T. Bhaskara Sudha, Dr. P. Aruna Devi, Dr. P.K. Jayalakshmi, Dr. Nalini Dutta, Sr. Daisy P.A., and Sr. Nancy Selva Rani K. We also extend our appreciation to the IQAC coordinator, organizing committee, resource speakers, and all those who contributed to the successful conduct of the conference.

Our heartfelt thanks go to all the authors for their valuable scholarly contributions, cooperation, and commitment to this publication. We hope this book inspires further research, scientific dialogue, and collaborative efforts towards a healthier society and a sustainable planet.

- Editors

Dr. Palukurty Mary Anupama

Dr. Mousami Shankar Addala

TABLE OF CONTENT

Sr. No.	Book Chapter and Author(s)	Page No.
1.	AI-ASSISTED BIOINFORMATICS EXPLORATION OF PLANT PROTEINS: MATURASE K (MATK) OF ANNONA MURICATA AS AN EMERGING RESEARCH MODEL Karuna Sri Thandu and Ramesh Malothu	1 – 4
2.	ENVIRONMENTAL SUSTAINABILITY, CLIMATE CHANGE AND PUBLIC HEALTH: FROM ENVIRONMENTAL RISK TO RESILIENT COMMUNITIES B. Gayathri	5 – 20
3.	TRANSFORMING FOOD SYSTEMS FOR SUSTAINABLE HEALTH AND WELL-BEING Dhagnapoor Prasanna Kumari and Jagannadham Karri	21 – 30
4.	EVOLUTIONARY TRAJECTORIES OF ANTIMICROBIAL RESISTANCE FROM SELECTION TO DISSEMINATION: A ONE HEALTH CONTINUUM Gundavarapu Bhargavi	31 – 39
5.	PROBIOTICS AND TRADITIONAL FERMENTED FOODS: MICROBIAL ALLIES FOR GUT AND METABOLIC HEALTH K. Sunita Raju	40 – 46
6.	INSIGHTS INTO AQUATIC FOODS AS A PATHWAY TO NUTRITION, SUSTAINABILITY AND INCLUSIVE FOOD SYSTEMS BEYOND PROTEIN SOURCE Y. Shanti Prabha	47 – 58
7.	ECO-ANXIETY AND ADAPTATION: PSYCHOLOGICAL RESPONSES TO CLIMATE CHANGE Kodukula Venkata Lakshmi Prudhvila	59 – 68
8.	CONVERGENCE OF SUSTAINABLE FOOD PACKAGING AND INFLUENCE OF CONSUMER PERCEPTION ON HEALTH Glory Joanna Manne and Karri Jagannadham	69 – 76
9.	PARENT-ADOLESCENT COMMUNICATION AND PROBLEMATIC DIGITAL BEHAVIORS AMONG ADOLESCENTS Angeline Bhaskar Busi and P. Mary Anupama	77 – 85

10.	FROM CLIMATE CRISIS TO HEALTH CRISIS: THE URGENT NEED FOR SUSTAINABLE ACTION	86 – 91
	Manasa Panduranga	
11.	UNDERSTANDING CLIMATE CHANGE THROUGH THE LENS OF PANCHA BHOO THAS OF THE HUMAN BODY: BREATH, FEVER, NUTRITION, INFECTION AND MIND	92 – 98
	Karakavalasa Joshitha	
12.	PLANT-DERIVED BIOACTIVE COMPOUNDS: FROM TRADITIONAL KNOWLEDGE TO NATURAL THERAPEUTIC DISCOVERY	99 – 105
	Gundavarapu Bhargavi	
13.	CLIMATE ANXIETY AND PSYCHOLOGICAL RESILIENCE: UNDERSTANDING MENTAL HEALTH IN AN ERA OF ENVIRONMENTAL CHANGE	106 – 113
	Shaista Bhartiya	
14.	NUTRACEUTICALS: CONCEPTS, CLASSIFICATION, HEALTH BENEFITS AND EMERGING APPLICATIONS FOR HUMAN HEALTH IN A CHANGING ENVIRONMENT	114 – 124
	Palla Sravani Sreeja, V. Sony, T. Gayatri, N. Nivya and Dipali Kumar Singh	
15.	INNOVATIONS IN FOOD AND NUTRITION FOR SUSTAINABLE LIVING: A BIOLOGICAL SCIENCE PERSPECTIVE	125 – 133
	Radhika Bandaroo	
16.	FROM CROP TO HUMAN HEALTH: ASSESSING THE NUTRITIONAL IMPACT OF BIOFORTIFICATION IN INDIA	134 – 140
	P. Sindhu Priya, K. Jagannadham, P. Deepa and B. Sagarika	
17.	INTEGRATED NUTRIENT MANAGEMENT IN SUSTAINABLE AGRICULTURE	141 – 149
	Landa Urmila	

AI-ASSISTED BIOINFORMATICS EXPLORATION OF PLANT PROTEINS: MATURASE K (MATK) OF *ANNONA MURICATA* AS AN EMERGING RESEARCH MODEL

Karuna Sri Thandu* and Ramesh Malothu

Department of Biotechnology,

Jawaharlal Nehru Technological University Kakinada, Andhra Pradesh, India - 533003

*Corresponding author E-mail: kk_sree@yahoo.com

Abstract

Medicinal plants continue to attract interest in biological research, and computational approaches have opened additional ways to study their genes and proteins. *Annona muricata* is well known for its medicinal importance, whereas its chloroplast-encoded Maturase K (MatK) protein is mainly recognized for its use in plant identification and phylogenetic studies. This chapter gives a simple overview of how routine bioinformatics methods and AI-assisted tools can be used together to study a plant protein from its sequence to a predicted three-dimensional structure. MatK is used here as an example rather than as evidence of any therapeutic effect. The discussion covers basic sequence characterization, physicochemical properties, structure prediction, evolutionary conservation and careful interpretation of computational results. It also considers how AI-supported analysis can help researchers organize information and identify questions for further investigation. Computational predictions are therefore treated as preliminary evidence that needs biological reasoning and, where required, experimental confirmation.

Keywords: *Annona muricata*, MatK, Maturase K, Bioinformatics, Artificial Intelligence, Protein Structure.

1. Introduction

Research on medicinal plants is no longer limited to the study of their chemical constituents. Genomics, proteomics and computational biology now make it possible to examine plant genes and proteins as well. These approaches can add another layer of biological understanding to plants such as *Annona muricata*, while experimental studies remain important for confirming biological significance.

Maturase K (MatK) is encoded by the chloroplast *matK* gene and is widely used in plant systematics. The *rbcl* and *matK* markers were recommended as a core DNA barcode for land plants [1]. From a bioinformatics point of view, MatK can also be studied through its sequence, basic physicochemical properties, evolutionary conservation and predicted three-dimensional structure [2,4]. In our published study on *A. muricata* MatK, AI-guided structure prediction and

conservation-based analysis were used to provide an initial view of the protein's structural organization [4]. In this chapter, the discussion is kept at a general level and focuses on established computational approaches and their responsible interpretation.

2. From Sequence to Structural Understanding

A protein sequence usually provides the first step in a computational analysis. From the amino-acid sequence, researchers can estimate properties such as molecular weight, theoretical isoelectric point, hydropathicity and indices related to stability. ProtParam is a widely used tool for obtaining several of these sequence-based values [2]. Such information is useful for preliminary characterization and for planning the next stage of analysis, although these values should not be considered a replacement for experimental measurements.

The use of AI has also strengthened protein-structure prediction. AlphaFold showed that machine-learning approaches can predict many protein structures with high accuracy and can provide confidence scores that help in judging different regions of a model [3]. In our published work on MatK, AI-guided structure prediction was examined together with evolutionary conservation to gain a broader structural view of the protein [4]. Results from this kind of analysis are most useful when they are used to frame further questions rather than to make unsupported claims about protein function.

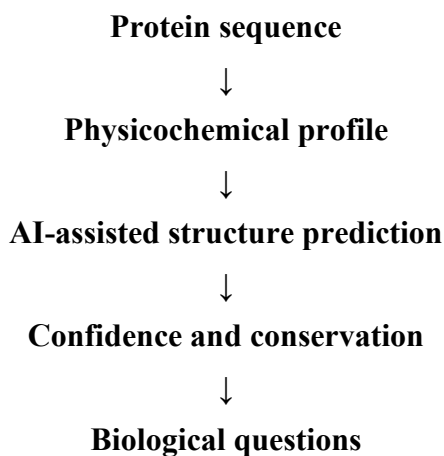


Figure 1: General workflow for preliminary AI-assisted plant-protein characterization

3. Biological Relevance and Scope

Computational analysis can be helpful at an early stage because it brings sequence and structural information together before more detailed laboratory work is planned. It can be used to compare related sequences, identify conserved regions and point to features that may deserve closer study. For a plant protein such as MatK, which is less frequently discussed from a structural perspective, this approach offers a practical way to move from a sequence record toward a better organized biological understanding.

However, a computational result should not be treated as direct evidence of therapeutic or disease-related activity. A predicted structure, a conserved region or a sequence-derived property

may support a research question, but its biological importance has to be established through appropriate evidence. Keeping this distinction clear allows AI-assisted bioinformatics to remain useful without overstating what a prediction can show.

4. Advantages, Challenges and Responsible Use of AI

AI-assisted bioinformatics can simplify several parts of early-stage analysis. It can help with sequence screening, visualization of predicted structures, comparison of conserved regions and selection of a smaller set of questions for further work. These features can be particularly useful in teaching, exploratory studies and research on proteins for which limited structural information is available.

At the same time, the output of these tools has to be interpreted carefully. Predictions may be affected by the quality of the input sequence, the assumptions of the model, the information available to the method and the confidence assigned to individual regions. Areas with low confidence should not be overinterpreted, and important observations should be checked by other approaches whenever possible. AI can support scientific analysis, but biological knowledge, critical judgment and experimental validation remain essential.

5. Future Perspectives

Plant-protein bioinformatics is likely to become more closely integrated as sequence analysis, comparative methods and AI-based structure prediction continue to improve. A practical way forward is to use these methods in stages: start with a reliable sequence, examine its basic properties, assess the predicted structure and confidence, compare conserved regions and then choose a small number of biologically meaningful questions for further investigation.

The usefulness of such work does not depend on applying as many tools as possible. It depends more on having a clear research question, choosing suitable methods and interpreting the output within its limitations. This approach can make AI-assisted bioinformatics easier to apply and scientifically more meaningful, especially when studying plant proteins that have received less attention.

Conclusion

AI-assisted bioinformatics offers a practical way to examine plant proteins from their amino-acid sequence to a predicted structural model. MatK of *Annona muricata* is a useful example because the gene is well established as a molecular marker, while the protein itself has received comparatively less attention in structural studies. Our published work provides an initial structural reference for this line of investigation [4]. The main strength of computational analysis is not that it provides final biological answers, but that it helps turn sequence information into clearer and testable research questions that can be explored in future studies.

References

1. CBOL Plant Working Group. (2009). A DNA barcode for land plants. *Proceedings of the National Academy of Sciences of the United States of America*, 106(31), 12794–12797. <https://doi.org/10.1073/pnas.0905845106>
2. Gasteiger, E., Hoogland, C., Gattiker, A., Duvaud, S., Wilkins, M. R., Appel, R. D., & Bairoch, A. (2005). Protein identification and analysis tools on the ExPASy server. In J. M. Walker (Ed.), *The proteomics protocols handbook* (pp. 571–607). Humana Press. <https://doi.org/10.1385/1-59259-890-0:571>
3. Jumper, J., Evans, R., Pritzel, A., *et al.* (2021). Highly accurate protein structure prediction with AlphaFold. *Nature*, 596, 583–589. <https://doi.org/10.1038/s41586-021-03819-2>
4. Malothu, R., & Thandu, K. S. (2026). In silico structure prediction of maturase K protein of *Annona muricata* from its amino acid sequence using AI-guided 3D structure prediction tool—AlphaFold and identification of its functional regions using the ConSurf server. *Research Journal of Biotechnology*, 21(3). <https://doi.org/10.25303/213rjbt044050>

ENVIRONMENTAL SUSTAINABILITY, CLIMATE CHANGE AND PUBLIC HEALTH: FROM ENVIRONMENTAL RISK TO RESILIENT COMMUNITIES

B. Gayathri

Government Degree College (Autonomous), Narsampet, Telangana

Corresponding author E-mail: dr.b.gayathri09@gmail.com

Abstract

Climate change is often presented as a problem of atmospheric science, energy policy, or environmental conservation. Yet its consequences are experienced most directly through human health. Extreme heat places pressure on the heart and kidneys, wildfire smoke aggravates respiratory illness, changing rainfall patterns affect water safety, and ecological disruption alters the distribution of infectious diseases. These effects rarely occur in isolation. They interact with poverty, housing quality, age, occupation, existing illness, access to healthcare, and the strength of local infrastructure. This chapter examines environmental sustainability as a practical public-health strategy rather than simply an ecological ambition. It considers the principal pathways through which climate change affects health and explores how renewable energy, sustainable urban planning, resilient food and water systems, ecosystem protection, and climate-ready healthcare can reduce risk. Four real-world case studies are used to connect the discussion with lived experience: Australia's 2019 to 2020 Black Summer bushfires, the European heat emergency of 2022, the 2021 Western North American heat dome, and the Netherlands' Room for the River programme. Together, these cases show that climate hazards become health disasters when they meet social vulnerability and inadequate preparation. They also demonstrate that well-designed adaptation can protect communities while improving environmental quality. The chapter concludes that public health must be embedded in climate policy, infrastructure planning, and sustainable development. Effective action requires cooperation among governments, health services, researchers, businesses, and communities. It must also address unequal exposure and unequal capacity to recover. Environmental sustainability is therefore not separate from public health. It is one of the conditions on which long-term health, security, and social well-being depend.

Keywords: Environmental Sustainability, Climate Change, Public Health, Climate Resilience, Renewable Energy, Sustainable Development, Environmental Justice, Health Adaptation.

1. Introduction

Climate change has moved from being a future possibility to a present challenge affecting communities in every region. The Intergovernmental Panel on Climate Change concluded that human activities, principally greenhouse gas emissions, have unequivocally caused global

warming. It also reported that human-caused climate change is already influencing weather and climate extremes around the world, with vulnerable communities experiencing disproportionate effects. Although the warming of the atmosphere is described in global averages, its effects are experienced in very personal ways. A person with asthma may struggle to breathe during a smoke event. An older adult living alone may be unable to cool their home during a heatwave. A family may lose access to medication when a flood closes local roads. A farmer may face reduced income and food availability after repeated drought. These examples show why climate change cannot be understood only through temperature records, emissions inventories, or environmental models. It must also be understood through the conditions in which people are born, live, work, and age.

The World Health Organization identifies clean air, safe drinking water, nutritious food, and secure shelter as essential foundations of good health, all of which are threatened by climate change. It also links climate change with illness and death arising from heatwaves, storms, floods, food-system disruption, water-borne and vector-borne diseases, and mental-health pressures. Environmental sustainability provides a way to address these connected risks. In simple terms, it means meeting present needs while preserving the environmental systems required by future generations. However, sustainability is not merely about using fewer resources. It also involves redesigning energy, transport, housing, agriculture, healthcare, and urban development so that societies can prosper without continually weakening the natural systems on which health depends.

This chapter develops three central arguments. First, climate change is a public-health issue because it affects environmental and social determinants of health. Second, the severity of a climate event depends not only on the physical hazard but also on exposure, vulnerability, and preparedness. Third, sustainability measures can produce immediate health benefits while reducing future climate risks. Cleaner energy, greener cities, safer housing, reliable public transport, protected water sources, and resilient healthcare systems are valuable not only because they reduce emissions, but because they improve everyday life.

2. Environmental Sustainability as a Health Foundation

Environmental sustainability refers to the responsible management of natural systems and resources so that ecological functions can continue over time. These functions include clean-air production, water filtration, soil formation, pollination, climate regulation, flood absorption, and the provision of food and raw materials. Human societies depend on these processes even when they are not visible in daily economic activity.

A sustainable society seeks to keep resource use and pollution within limits that ecosystems can tolerate. This includes reducing dependence on fossil fuels, preventing avoidable waste, protecting biodiversity, using land responsibly, and designing production systems around

efficiency, repair, reuse, and recovery. Sustainability also has a social dimension. A technically efficient policy cannot be considered fully sustainable if it transfers health risks to low-income neighbourhoods, displaces vulnerable communities, or makes essential energy and food unaffordable.

The relationship between sustainability and health can be understood through three levels:

- 1. Prevention of environmental exposure:** Lower emissions and better waste management reduce exposure to air, water, and soil pollution.
- 2. Promotion of healthy living conditions:** Walkable neighbourhoods, public transport, green space, safe housing, and nutritious food support physical and mental health.
- 3. Protection against future shocks:** Resilient infrastructure, emergency planning, diverse food systems, and secure water supplies help communities withstand climate-related disruption.

Table 1: Dimensions of environmental sustainability and their health significance

Sustainability Dimension	Illustrative Action	Environmental Value	Potential Public-Health Value
Clean energy	Replacing high-emission energy with renewable sources	Reduces greenhouse gas emissions and air pollution	Lowers exposure to harmful pollutants
Sustainable transport	Expanding public transport, walking, and cycling networks	Reduces vehicle emissions and congestion	Supports physical activity and cleaner air
Water stewardship	Protecting catchments and improving water efficiency	Conserves freshwater resources	Supports safe and reliable drinking water
Sustainable food systems	Improving soil health and reducing food loss	Protects land and reduces resource pressure	Strengthens nutrition and food security
Biodiversity protection	Conserving habitats and restoring ecosystems	Maintains ecological functions	Supports water quality, food production, and disease regulation
Circular resource use	Repairing, reusing, and recycling materials	Reduces extraction and waste	Limits exposure to pollution and hazardous waste
Climate-resilient healthcare	Preparing facilities and supply chains for hazards	Reduces disruption and resource loss	Maintains essential care during emergencies

Environmental sustainability should therefore be seen as both a preventive and protective approach to health. It prevents harm by reducing environmental degradation and protects people by strengthening the systems on which they rely.

3. How Climate Change Becomes a Health Risk

Climate change does not produce a single, uniform pattern of illness. Its effects emerge through several connected pathways, and these pathways differ according to geography, infrastructure, social conditions, and population health.

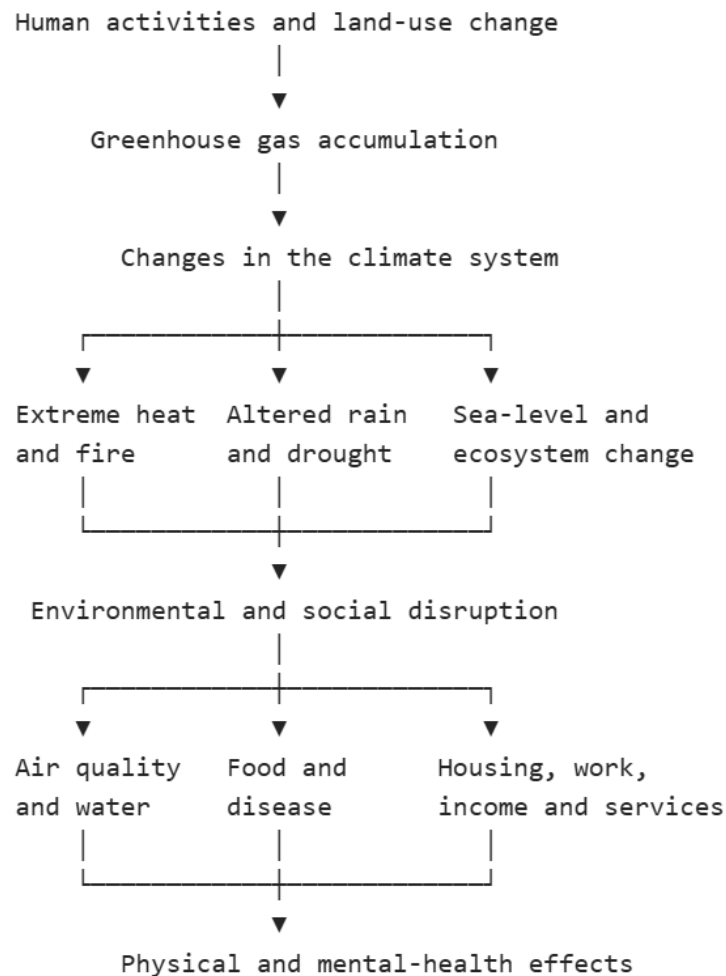


Figure 1: Climate-to-health pathway

The figure highlights an important distinction. A climatic hazard does not automatically become a disaster. Damage increases when people are exposed, when they have limited capacity to protect themselves, and when essential systems fail to respond. This is why the same heatwave can have markedly different consequences across neighbourhoods.

3.1 Extreme Heat

Heat affects the body's ability to regulate its internal temperature. Extended exposure can contribute to dehydration, heat exhaustion, heatstroke, cardiovascular strain, and kidney stress. People with chronic illnesses, older adults, young children, outdoor workers, and those taking certain medications may face greater risk.

Housing conditions are particularly important. Insulation, ventilation, access to cooling, building orientation, tree cover, and the retention of heat by surrounding surfaces can determine whether a home remains safe. Heat risk is therefore partly a medical concern, but it is also an issue of housing, urban design, energy affordability, and social connection.

3.2 Air Pollution and Respiratory Health

Climate change and air pollution share important causes, especially the extraction and burning of fossil fuels. Higher temperatures can also influence ground-level ozone, while drought and extreme heat can contribute to conditions favourable to wildfire. Smoke contains fine particulate matter capable of travelling considerable distances and entering deep into the lungs.

The health consequences can include worsening asthma, respiratory irritation, cardiovascular stress, and increased demand for health services. Cleaner energy policies can therefore produce a dual benefit by addressing greenhouse gas emissions while improving local air quality. The World Health Organization explicitly identifies major health co-benefits from measures that reduce the burning of polluting fuels and encourage public and active transport.

3.3 Water Safety and Availability

Climate change influences the water cycle through altered rainfall, drought, flooding, snow and ice loss, and saltwater intrusion in some coastal areas. Water scarcity can reduce hygiene, affect agriculture, and increase competition for limited supplies. At the other extreme, flooding can overwhelm drainage and sanitation systems, contaminate water sources, and interrupt treatment facilities.

Water-related risks are shaped by public infrastructure. Communities with reliable treatment, monitoring, drainage, and emergency distribution systems are better positioned to respond. Those with ageing infrastructure or limited public resources may experience longer and more severe disruption.

3.4 Food Security and Nutrition

Food systems depend on stable seasons, healthy soil, adequate water, pollination, transport, storage, and functioning markets. Extreme heat, drought, floods, changing pest patterns, and ecosystem degradation can disturb several parts of this system at once.

The resulting health effects may include reduced dietary quality, food-price pressure, undernutrition, and livelihood stress. Sustainable agriculture can help by improving soil condition, conserving water, diversifying crops, reducing excessive chemical use, and strengthening local resilience. However, sustainable production alone is insufficient if healthy food remains economically or geographically inaccessible.

3.5 Infectious Disease

Temperature and rainfall influence the habitats, breeding cycles, and seasonal activity of mosquitoes, ticks, and other disease vectors. Flooding and inadequate sanitation can also

increase exposure to water-borne pathogens. Climate change does not independently determine where every outbreak will occur, but it can alter the environmental suitability for transmission.

Disease outcomes also depend on surveillance, vaccination where available, housing, sanitation, healthcare access, public awareness, and vector-control capacity. Climate-informed health monitoring can help authorities identify changing patterns and act earlier.

3.6 Mental Health and Well-Being

Climate-related health effects are not limited to physical illness. People who experience fires, floods, displacement, livelihood loss, or prolonged drought may face anxiety, grief, depression, trauma, and uncertainty. Health workers and emergency responders can also experience cumulative psychological pressure.

Mental-health effects may continue after physical infrastructure has been repaired. Recovery planning should therefore include accessible and culturally appropriate psychosocial support, community connection, and long-term follow-up, rather than treating mental health as a secondary concern.

Table 2: Climate hazards, health pathways, and protective responses

Climate-Related Hazard	Exposure Pathway	Possible Health Consequence	Protective Response
Extreme heat	Hot homes, outdoor work, urban heat retention	Heat illness and worsening chronic disease	Heat alerts, cool buildings, tree cover, outreach
Wildfire smoke	Fine particles and gases in indoor and outdoor air	Respiratory and cardiovascular effects	Air-quality warnings, clean-air spaces, filtration
Flooding	Contaminated water, damaged services, displacement	Injury, infection, stress, interrupted care	Drainage, resilient facilities, safe-water plans
Drought	Water scarcity and reduced agricultural production	Poor nutrition, livelihood stress, hygiene challenges	Water efficiency, diversified crops, social support
Ecological change	Shifts in vectors and pathogen environments	Changing infectious-disease patterns	Surveillance, vector control, public communication
Coastal change	Flooding, erosion, salinity, relocation	Injury, displacement, grief, loss of livelihood	Managed adaptation, protective infrastructure, planning

4. Real-World Case Studies

The following cases illustrate how climatic hazards interact with housing, healthcare, urban form, social inequality, and institutional preparation. They also show that climate-health policy requires more than an emergency response. Long-term risk reduction must influence how communities are built and governed.

4.1 Australia's Black Summer bushfires, 2019 to 2020

Australia's 2019 to 2020 bushfire season, widely known as Black Summer, demonstrated that the health effects of fire extend far beyond the fire front. Large areas experienced prolonged smoke exposure, including communities located a considerable distance from active fires.

The Australian Institute of Health and Welfare found clear associations between increased bushfire activity, poor air quality, and people seeking health assistance. Its assessment covered emergency-department presentations, asthma medicines, mental-health service use, and general-practice visits. The report also identified a clear relationship between poor air quality and respiratory emergency-department visits in New South Wales.

The experience is significant for public health because smoke does not respect administrative boundaries. A hospital may remain physically untouched by fire while receiving additional respiratory cases. A person may not be evacuated yet may still face prolonged exposure. Public messaging must therefore address both immediate fire safety and the less visible risks associated with smoke.

Black Summer also revealed the importance of continuity planning. Communities affected by fire may simultaneously face damaged roads, communication interruptions, displaced residents, reduced access to medication, and pressure on local health workers. Recovery cannot be limited to rebuilding structures. It must also consider mental health, community cohesion, environmental restoration, and the needs of people whose work or housing has been disrupted.

Key lessons

- Air-quality monitoring should be connected to timely and accessible health advice.
- Healthcare services need surge plans for respiratory and cardiovascular demand.
- Public buildings can be considered as potential clean-air spaces during severe smoke.
- Bushfire preparation should include medication continuity and psychosocial support.
- Land management, emissions reduction, emergency response, and community education need to operate together.

4.2 The European heat emergency of 2022

The European summer of 2022 made the health consequences of extreme heat difficult to ignore. A study published in *Nature Medicine* analysed mortality data covering hundreds of regions across 35 European countries. It estimated 61,672 heat-related deaths between 30 May and 4

September 2022 and called for stronger heat-surveillance systems, prevention plans, and long-term adaptation.

The event illustrates why preparedness cannot rely solely on general weather forecasts. A temperature warning is useful, but its protective value depends on what happens next. Health services need thresholds for action. Local authorities need ways to contact people at risk. Care facilities need safe indoor-temperature plans. Employers need procedures for outdoor and heat-exposed work. Residents need practical information that is understandable, locally relevant, and available in appropriate languages.

Urban design also shapes heat exposure. Dense built environments can retain heat, particularly where shade and vegetation are limited. Apartments may remain hot overnight, reducing the body's opportunity to recover. Sustainable urban planning can address this through tree canopy, reflective or shaded surfaces, ventilation, accessible green space, and building standards suited to a warming climate.

The European experience also underlines the limits of treating heat as an unusual seasonal inconvenience. Repeated heat emergencies require permanent public-health capability rather than temporary improvisation.

Key lessons

- Heat-health action plans need clear responsibilities and activation thresholds.
- Targeted welfare checks may be required for isolated and medically vulnerable people.
- Hospitals and residential-care facilities need reliable cooling and contingency arrangements.
- Long-term adaptation should improve buildings and neighbourhoods, not merely expand emergency messaging.
- Heat policy should consider affordability so that protection does not depend solely on household income.

4.3 The 2021 Western North American heat dome

In late June 2021, British Columbia experienced an unprecedented heat event. The British Columbia Coroners Service reviewed the deaths of 619 people associated with the extreme heat period from 25 June to 1 July 2021.

Research from greater Vancouver found that heat-dome mortality risk was associated with material and social deprivation, lower neighbourhood greenness, age, and high indoor temperatures. The authors recommended focusing public-health responses on highly deprived neighbourhoods with low air-conditioning prevalence and continuing the promotion of urban green space.

This case changes the way heat vulnerability should be understood. Risk is not simply a matter of whether a person knows that the weather is hot. Someone may understand the warning but

lack a safe place to go. They may be physically unable to travel, socially isolated, concerned about energy costs, or living in a building that accumulates heat. Effective adaptation must therefore move beyond individual advice such as drinking water and staying indoors. In some buildings, staying indoors may not be protective.

The event also demonstrates the importance of indoor-temperature awareness. Conventional weather systems measure outdoor conditions, but people spend much of their time inside buildings. Housing design and indoor monitoring should become part of heat-health planning, especially for older housing stock and upper-floor apartments.

Key lessons

- Heat vulnerability mapping should include deprivation, housing, greenness, and social isolation.
- Emergency plans should identify safe, accessible, and genuinely cool locations.
- Community organisations can help with outreach to people who may not respond to digital alerts.
- Building codes and retrofit programmes should address overheating as well as cold-weather efficiency.
- Urban greening should be directed towards neighbourhoods with the greatest exposure and least existing protection.

4.4 The Netherlands' Room for the River programme

Not every useful climate case study begins with a health disaster. The Netherlands' Room for the River programme offers an example of anticipatory adaptation. Rather than relying only on continually raising barriers, the programme created additional room for rivers during high-water conditions.

According to Rijkswaterstaat, measures were implemented at 30 locations. These included moving dykes inland, constructing flood channels, and lowering floodplains so that rivers could spread more safely during periods of high water and reduce pressure on dykes.

The programme is relevant to public health even though it is primarily described as flood-risk management. Reducing flood risk can protect homes, drinking-water systems, roads, sanitation, healthcare access, and community stability. The case also illustrates a broader sustainability principle: human development can sometimes be made safer by working with natural processes rather than attempting to constrain them entirely.

Room for the River shows the value of long-term spatial planning. Land-use decisions made today determine future exposure. Allowing high-risk areas to become densely developed may create vulnerabilities that are expensive and difficult to reverse. By contrast, planned flood-storage areas, restored floodplains, and carefully located infrastructure can reduce risk before an emergency develops.

It is important not to treat the Dutch approach as a model that can simply be copied into every setting. River systems, governance arrangements, land ownership, financing, and community priorities differ. Its transferable lesson is the value of integrated planning, not the automatic replication of individual engineering measures.

Key lessons

- Climate adaptation should be incorporated into land-use planning before development occurs.
- Nature-based and engineered measures can be combined.
- Flood planning should protect essential health, water, transport, and communication services.
- Community participation is important where adaptation changes land use or livelihoods.
- Preventive investment can reduce the human consequences of future hazards.

Table 3: Comparative analysis of the four case studies

Case	Main Hazard	Health Significance	Vulnerability Revealed	Principal Adaptation Lesson
Australian Black Summer	Bushfire and prolonged smoke	Respiratory demand, service disruption, mental-health pressure	Chronic illness, exposure to smoke, disrupted communities	Link fire planning with air quality, healthcare continuity, and recovery support
Europe, 2022	Extended extreme heat	Large heat-related mortality burden	Age, chronic illness, unsafe buildings, urban heat	Strengthen heat plans and redesign neighbourhoods and buildings
Western North American heat dome	Severe and persistent heat	High mortality in British Columbia	Deprivation, low greenness, unsafe indoor heat, isolation	Target community protection using social and housing data
Room for the River	River flooding risk	Protection of living conditions and essential systems	Development in flood-prone landscapes	Plan spatially and create room for natural water processes

5. Sustainable Approaches to Protect Public Health

5.1 Clean and Renewable Energy

Moving away from polluting fossil-fuel systems is essential for reducing greenhouse gas emissions. It can also improve health by reducing exposure to harmful air pollution. This makes

clean-energy policy one of the clearest examples of climate action with immediate public-health value.

A fair transition requires more than building renewable-generation capacity. It also involves energy efficiency, reliable networks, affordable access, workforce planning, and support for communities affected by industrial change. If clean technologies are available only to wealthier households, health inequalities may persist.

5.2 Healthy and Climate-Ready Cities

Cities concentrate people, buildings, transport, and economic activity. This makes them centres of both climate risk and climate solutions. Compact, connected neighbourhoods can reduce travel emissions, but density must be accompanied by ventilation, shade, green space, safe walking routes, public transport, and services close to where people live.

Green infrastructure can provide shade, support biodiversity, improve recreational opportunities, and assist with stormwater management. However, the distribution of green space matters. Planting programmes should prioritise areas with high heat exposure, low canopy coverage, and greater social vulnerability.

5.3 Resilient Food Systems

Food-system resilience can be strengthened through crop diversity, soil conservation, water efficiency, responsible nutrient use, reduced food loss, and better storage and distribution. Supporting local production can be useful in some contexts, but resilience should not be confused with complete self-sufficiency. Diverse regional and international supply networks may also protect communities when one area experiences crop failure.

Nutrition must remain central. A food system that is environmentally efficient but does not provide affordable and culturally appropriate nutrition cannot be considered healthy or equitable.

5.4 Water-Sensitive Planning

Sustainable water management links catchment protection, conservation, drainage, wastewater treatment, flood management, and drought preparation. Urban areas can use permeable surfaces, wetlands, rainwater systems, and vegetation to slow runoff and reduce pressure on drainage networks.

Health authorities should be involved in water planning because failures can influence drinking-water safety, sanitation, infectious disease, food production, and continuity of clinical services.

5.5 Climate-Resilient and Environmentally Sustainable Healthcare

Healthcare systems face a dual responsibility. They must remain operational during climate emergencies while reducing their own environmental impact. The World Health Assembly has recognised that climate change threatens health facilities and health systems, while modern health systems also contribute to environmental pollution and global emissions.

Resilience measures may include assessing facility exposure, protecting backup power and water, securing medicine supply chains, preparing for workforce disruption, strengthening disease surveillance, and incorporating climate risk into emergency exercises. Sustainability measures can include efficient buildings, lower-waste procurement, safer waste management, and cleaner energy.

The two objectives should be pursued together. A low-emission facility that cannot operate during a flood is not resilient, while an emergency-ready facility with unnecessarily high pollution and waste is not environmentally sustainable.

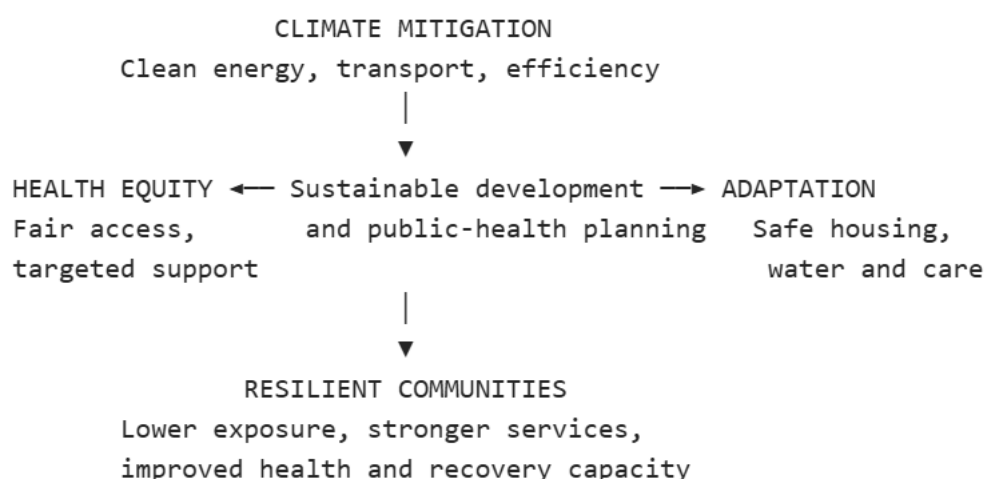


Figure 2: Integrated climate and health response

6. Governance, Policy, and International Cooperation

Climate-health risks cross traditional administrative boundaries. An extreme event may involve environmental agencies, hospitals, emergency services, housing providers, transport authorities, water utilities, schools, employers, and community organisations at the same time. Fragmented governance can leave significant gaps.

An integrated policy approach should include:

- Climate-risk assessment within public-health plans;
- Health-impact assessment within climate and infrastructure policy;
- Defined institutional responsibilities during emergencies;
- Accessible risk communication;
- Long-term funding for adaptation;
- Routine monitoring and evaluation;
- Community participation in planning;
- Specific measures for populations facing greater exposure or fewer resources.

International frameworks can guide national action, but implementation takes place largely through local systems. Global emissions commitments will not by themselves cool an unsafe

apartment during a heatwave. Similarly, a local cooling centre cannot address the long-term rise in climate risk. Mitigation and adaptation are complementary, and both are necessary.

Equity must be treated as a core policy requirement. Communities that have contributed least to greenhouse gas emissions may experience severe consequences while possessing fewer financial and institutional resources for adaptation. Within countries, people living in insecure housing or polluted neighbourhoods may face greater exposure. A fair response directs resources according to need and includes affected communities in decisions.

7. A Practical Framework for Climate-Health Action

The case studies suggest a six-stage framework that governments and organisations can use when developing climate-health strategies.

Stage 1: Identify Hazards

Map the climate-related hazards relevant to the area, such as heat, smoke, flood, drought, coastal inundation, or changing infectious-disease conditions.

Stage 2: Understand Exposure

Identify where people, healthcare facilities, water systems, transport routes, housing, and critical services intersect with those hazards.

Stage 3: Assess Vulnerability

Consider age, health status, income, occupation, housing quality, mobility, language, social isolation, and access to services. Vulnerability should not be treated as a personal weakness. It frequently reflects structural and environmental conditions.

Stage 4: Co-Design Interventions

Work with communities, health professionals, infrastructure providers, and local organisations to select measures that are practical and acceptable.

Stage 5: Implement Mitigation and Adaptation Together

Where possible, choose interventions that lower emissions and improve health while protecting people from unavoidable hazards. Public transport, energy-efficient housing, urban greening, and resilient renewable power can produce several benefits at once.

Stage 6: Monitor Outcomes and Revise

Evaluate whether the intervention actually reduces exposure and improves health. Monitoring should also examine whether benefits are reaching the intended communities and whether unintended disadvantages have appeared.

Indicators should be interpreted cautiously. A reduction in hospital presentations does not always mean exposure has fallen, as access barriers may also influence service use. Quantitative data should therefore be considered alongside community experience and qualitative evaluation.

Table 4: Example indicators for monitoring climate-health action

Action Area	Process Indicator	Health or Resilience Indicator
Heat preparedness	Coverage of heat-alert and outreach plans	Heat-related service demand and indoor-temperature safety
Wildfire smoke	Availability of air-quality communication and clean-air spaces	Respiratory presentations during smoke episodes
Healthcare resilience	Facilities with climate-risk and continuity assessments	Maintenance of essential services during hazards
Urban greening	Canopy expansion in high-exposure neighbourhoods	Shade access and local heat exposure
Water resilience	Critical systems with drought and flood plans	Continuity of safe-water supply
Community engagement	Participation of affected groups in planning	Accessibility and uptake of protective services

8. Discussion

The four cases examined in this chapter show that climate-related illness is shaped by more than the severity of weather. Australia's Black Summer highlighted the broad geographic reach of smoke and the prolonged demands placed on communities and health services. The European heat emergency demonstrated the scale of mortality that can arise even in regions with established public-health systems. The Western North American heat dome drew attention to indoor overheating, neighbourhood greenness, deprivation, and social vulnerability. The Netherlands showed how environmental planning can reduce risk before a health emergency occurs.

A consistent lesson is that emergency response, while essential, is not enough. Ambulances, hospitals, alerts, and evacuation plans respond after risk has already intensified. Prevention begins much earlier through building standards, land-use policy, clean energy, social protection, public transport, tree cover, water security, healthcare planning, and environmental conservation. Another lesson is that individual behaviour has limits. Public advice often tells people to stay cool, avoid smoke, conserve water, or prepare emergency supplies. Such guidance can be useful, but it assumes that people have safe housing, money, mobility, information, and social support. Public policy must create conditions in which protective behaviour is possible.

The cases also demonstrate why climate policy should communicate health benefits more clearly. Reduced emissions may seem abstract when discussed only in tonnes of carbon dioxide. Cleaner air, safer homes, quieter streets, accessible parks, secure water, and reliable healthcare are tangible outcomes. Presenting climate action through these immediate benefits may encourage broader engagement.

9. Future Directions

Future research and policy should increasingly focus on compound risks. Heat may occur alongside wildfire smoke. Flooding may coincide with power failure. Drought may interact with food-price increases and mental-health stress. Planning based on one hazard at a time may underestimate these combined effects.

Better local data will also be important. National averages can hide differences between neighbourhoods. Climate-health surveillance should connect environmental information with health, housing, infrastructure, and social data while maintaining privacy and ethical safeguards. Greater attention is needed for implementation. Evidence about what should be done is growing, but communities also need knowledge about financing, governance, workforce capacity, maintenance, and public participation. Adaptation measures must remain effective over time rather than ending after a short pilot programme.

Finally, climate education should extend beyond environmental science. Health professionals, planners, architects, engineers, teachers, business leaders, and emergency managers all influence climate resilience. Interdisciplinary learning is essential because no single profession controls all the systems that determine health.

Conclusion

Environmental sustainability, climate change, and public health are inseparable. Climate change affects health through heat, air pollution, water disruption, food-system pressure, infectious disease, displacement, and psychological stress. These impacts are intensified by inequality, unsafe housing, fragile infrastructure, existing illness, and limited access to services.

The case studies in this chapter provide both warnings and practical lessons. Black Summer showed how wildfire smoke can become a widespread public-health emergency. The European heat of 2022 revealed the continuing mortality burden of extreme temperatures. The 2021 heat dome showed that indoor conditions and social disadvantage can determine who is most at risk. Room for the River illustrated the value of planning ahead and making space for natural processes.

Sustainability should therefore be understood as an investment in health. Clean energy, resilient housing, safe water, sustainable food systems, green urban environments, ecosystem protection, and climate-ready healthcare can reduce future danger while improving present-day well-being. The most effective policies will combine mitigation, adaptation, and equity rather than treating them as separate agendas.

Protecting public health in a changing climate will require sustained cooperation across governments, communities, businesses, research institutions, and healthcare organisations. It will also require a shift from reacting to disasters towards designing healthier and more resilient communities before emergencies occur. The central message is straightforward: caring for

environmental systems is not separate from caring for people. It is one of the most important ways in which societies can protect human life and well-being across generations.

References

1. Australian Institute of Health and Welfare. (2020). *Australian bushfires 2019–20: Exploring the short-term health impacts*. Australian Government.
2. Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Pegenaute, F., Herrmann, F. R., Robine, J. M., Basagaña, X., Tonne, C., Antó, J. M., & Achebak, H. (2023). Heat-related mortality in Europe during the summer of 2022. *Nature Medicine*, 29, 1857–1866.
3. British Columbia Coroners Service. (2022). *Extreme heat and human mortality: A review of heat-related deaths in B.C. in summer 2021*. Government of British Columbia.
4. Henderson, S. B., McLean, K. E., Lee, M. J., & Kosatsky, T. (2022). Analysis of community deaths during the catastrophic 2021 heat dome: Early evidence to inform the public health response during subsequent events in greater Vancouver, Canada. *Environmental Epidemiology*, 6(1).
5. Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Summary for policymakers*. IPCC.
6. Rijkswaterstaat. (n.d.). *Room for the River*. Government of the Netherlands.
7. World Health Organization. (2022). *Review of IPCC evidence 2022: Climate change, health and well-being*. WHO.
8. World Health Organization. (2024). *Climate change and health: World Health Assembly Resolution WHA77.14*. WHO.
9. World Health Organization. (n.d.). *Climate change*. WHO.

TRANSFORMING FOOD SYSTEMS FOR SUSTAINABLE HEALTH AND WELL-BEING

Dhagnapoor Prasanna Kumari* and Jagannadham Karri

Department of Clinical Nutrition Dietetics and Food Science,

School of Allied and Healthcare Sciences,

Malla Reddy University, Hyderabad, Telangana-500043, India

*Corresponding author E-mail: prasannadlr2001@gmail.com

Abstract

Food systems are central to achieving the Sustainable Development Goals (SDGs), particularly those related to poverty and hunger eradication, nutrition and health improvement, and environmental sustainability. Transforming food systems to deliver healthy and equitable diets while remaining within planetary boundaries requires coordinated action across multiple interconnected domains. This review identifies six critical areas for food-system transformation: reinventing agriculture, creating food environments that support healthy diets, mitigating climate change, engaging the private sector responsibly, strengthening public policy and governance, and implementing true-cost accounting of food. Within this broader context, food loss and waste (FLW) represent major global challenges with significant implications for food security, environmental sustainability, public health, and economic efficiency. Persistent gaps in data quality, behavioural research, policy implementation, and the adoption of circular-economy approach further constrain effective FLW reduction. This review examines the interconnected environmental, health, and economic consequences of food loss and waste, while also considering the influence of governance structures and cultural contexts, particularly in developing countries. The findings highlight the need for transparent, evidence-based, and context-specific policies that integrate FLW reduction into national strategies for food security, climate-change mitigation, sustainable resource management, and public health. A systems-based and multisectoral approach is essential to achieving resilient, sustainable, and equitable food systems.

Keywords: Food System, Sustainable Development Goals, Food Security, Public Health, Healthy Diets.

Introduction

Food waste and food losses are closely related yet distinct concepts that reflect the inefficient utilization of food resources. Food losses primarily occur at the earlier stages of the food supply chain, including production, post-harvest handling, storage, and processing. These losses are commonly attributed to factors such as pest infestation, spoilage, inadequate storage and

transportation infrastructure, and limitations in appropriate technologies (Mesterházy *et al.*, 2020; Stathers and Mvumi, 2020). In contrast, food waste predominantly occurs at the retail and consumer levels and may result from over-purchasing, improper storage, product expiration, and aesthetic standards that lead to the disposal of otherwise edible food. Both food losses and food waste contribute to the unnecessary depletion of global food resources; however, food losses are generally associated with systemic inefficiencies across the food supply chain, whereas food waste is more frequently influenced by individual behaviours, practices, and consumption choices (Wright, 2022; Urugo *et al.*, 2024).

Food waste arises from a range of interconnected everyday household practices, including food purchasing, storage, preparation, cooking, and consumption. The integration of these activities into daily routines can limit consumers' awareness of the diverse factors that contribute to food waste. Sociological research on food waste emphasizes the social organization of household food practices and highlights how cultural, social, material, and temporal dimensions shape decisions regarding whether food is perceived as edible or inedible. Such perspectives provide a contextual understanding of the practices and circumstances through which food waste is generated in everyday life (Hebrok and Boks, 2017).

The material characteristics of food, together with infrastructural conditions such as living arrangements, household storage capacity, geographical accessibility to food retailers, and available transportation facilities, can significantly influence food waste by shaping everyday household routines and food-related practices (Soma, 2020). Consumer decisions and practices concerning the type and quantity of food purchased, the handling of food prior to reaching the household, its storage after purchase, and meal planning are important factors in preventing and reducing food waste. Appropriate management of these practices can contribute substantially to minimizing avoidable food waste at the household level (Liegeard and Manning, 2020).

Education also plays an important role in influencing awareness, knowledge, and attitudes towards food waste. Individuals with lower levels of education may have limited knowledge regarding appropriate food storage practices, meal planning, and the interpretation of food expiration labels, potentially resulting in the unnecessary disposal of edible food. A European survey reported that more than 60% of consumers discarded food that was still safe for consumption due to misinterpretation of food labelling (Graham-Rowe *et al.*, 2014)

Environmental Burden and Ecological Implications of Food Waste

Food waste represents a significant contributor to global environmental degradation and is associated with approximately 8–10% of total anthropogenic greenhouse gas (GHG) emissions. These emissions arise throughout the food supply chain and are particularly associated with the decomposition of discarded food in landfills, which generates substantial quantities of methane, a potent greenhouse gas (Hickey and Ozbay, 2014).

If food waste were considered as an individual source of greenhouse gas emissions, it would rank among the largest contributors globally, following major national emitters such as China and the United States (Lin *et al.*, 2013; Shen *et al.*, 2024).

In the United States alone, food waste is estimated to generate more than 170 million metric tonnes of carbon dioxide equivalent (CO₂e) emissions annually, representing a substantial increase from earlier estimates of approximately 80 million tonnes when landfill-related emissions were excluded. The environmental consequences of food waste extend beyond GHG emissions and include substantial losses of freshwater and agricultural land, as well as adverse effects on ecosystems and biodiversity (Bhatt, 2023).

Furthermore, the improper disposal of food waste can contribute to soil and water contamination and increase methane emissions, particularly in urban areas where waste collection, treatment, and disposal systems are inadequate. Poorly managed food waste therefore represents an important environmental concern, with implications for climate change, natural resource depletion, pollution, and ecosystem health (MEDA, 2023).

Social Impacts of Food Waste

Food waste represents a significant missed opportunity to address global hunger and promote greater equity in food access. Although global food production has the potential to provide sufficient food for a population of approximately 10 billion people, a substantial proportion of the world's population continues to experience food insecurity. In 2023, nearly 735 million people were estimated to be facing hunger, highlighting the persistent disparity between food availability and equitable access to adequate nutrition (Hunger and Insecurity, 2024).

Public Health Implications of Food Waste

Food waste can have both direct and indirect implications for human health. Globally, the decomposition of organic food waste in landfills generates methane and other emissions that contribute to climate change. These environmental changes may increase the risks associated with heat stress, respiratory disorders, and vector-borne diseases, thereby creating additional public health concerns (Aziz *et al.*, 2020).

In the United States, the improper disposal of food waste can place additional pressure on municipal waste-management infrastructure and contribute to the formation of contaminated leachate, which may pose a risk to underlying soil and groundwater resources. Similarly, in many African countries, inadequate food-waste management is associated with environmental contamination, reduced access to safe water, poor sanitation conditions, and increased exposure to disease-causing agents. Thus, effective food-waste management is important not only for environmental protection but also for safeguarding public health and improving sanitation conditions (Fami *et al.*, 2019).

Benefit-Cost Perspectives on Global Food Loss and Waste Reduction

A benefit–cost ratio represents the relationship between the financial benefits generated and the financial costs incurred through food loss and waste (FLW) reduction actions or programmes (Clowes *et al.*, 2019).

Evidence indicates that reducing global FLW can generate substantial economic, environmental, and social benefits that may outweigh the costs associated with implementing reduction measures (Luo *et al.*, 2022).

Consequently, FLW reduction can provide a potential “triple win” by strengthening economic efficiency, improving food security, and reducing environmental pressures. From an economic perspective, the Food and Agriculture Organization (FAO) estimates that approximately one-third of the food produced globally is lost or wasted, representing an economic loss of around US\$1 trillion annually. Such losses extend beyond the value of the food itself and include the inefficient use of labour, energy, water, land, and other resources invested throughout the food supply chain (FAO, 2023; Nénert *et al.*, 2025).

Investments in improved storage facilities, transportation systems, processing technologies, and market access, particularly in developing countries, can contribute to reducing post-harvest losses and improving the overall efficiency and resilience of food systems (Goswami, 2022).

From an environmental perspective, reducing FLW can contribute substantially to the mitigation of greenhouse gas emissions and the conservation of natural resources. Food decomposition in landfills produces methane, while food production and disposal throughout the supply chain are associated with substantial demands for land and water and may contribute to deforestation and biodiversity loss. Reducing FLW can therefore decrease the need for surplus food production, conserve natural resources, reduce associated emissions, and support climate-change mitigation efforts (Berry, 2020; Hariram *et al.*, 2023; FAO, 2023).

The reduction of FLW can also contribute to improved food security by redirecting safe and edible surplus food towards food-insecure populations, thereby increasing the availability of food without necessarily requiring additional agricultural production. Such redistribution can be supported through food banks, community kitchens, food recovery programmes, and other redistribution networks. From a social perspective, these interventions can contribute to more equitable access to food while strengthening the resilience and sustainability of food systems, particularly in communities affected by food insecurity and undernutrition (FAO, 2024; Sharma *et al.*, 2024).

Role of Food Loss and Waste Reduction in Strengthening Food Security and Global Nutrition

Enhancing global nutrition and food security is essential for achieving sustainable development and improving the well-being of populations worldwide with continued population growth,

climate change, and rapid urbanization, ensuring consistent access to sufficient, safe, and nutritious food has become an increasingly important global priority. Sustainable agricultural innovations, including climate-smart farming practices and the adoption of resilient crop varieties, can contribute to increasing food production, particularly in vulnerable regions. In addition, reducing food loss and waste (FLW), promoting equitable food distribution, strengthening social protection systems, and improving nutritional education are important measures for enhancing food security and nutrition (Pérez-Escamilla, 2017).

Food security is generally understood through four interconnected dimensions: availability, access, utilization, and stability. Food loss and waste adversely affect food security by reducing the quantity of food available for human consumption and diminishing the efficiency of food systems. Consequently, reducing FLW can contribute positively to all four dimensions and represents an important strategy for strengthening food security and improving the sustainability of global food systems (Makate *et al.*, 2019).

Food Availability

Reducing FLW can increase the quantity of food available for human consumption without requiring additional agricultural production. Approximately one-third of food produced globally, equivalent to about 1.3 billion tonnes annually, is estimated to be lost or wasted. Recovering and effectively utilizing a proportion of this food could therefore increase the available food supply, particularly in regions where substantial losses occur during production, post-harvest handling, storage, processing, and distribution as a result of inadequate infrastructure and technology (FAO, 2017; Santeramo and Lamonaca, 2021).

Food Access

FLW reduction can improve physical and economic access to food, particularly among low-income and vulnerable populations. Greater efficiency throughout the food supply chain can reduce resource wastage and potentially contribute to improved market efficiency, affordability, and price stability. Furthermore, redirecting safe and edible surplus food through appropriate food recovery and redistribution systems can improve access to nutritious food among food-insecure populations (Santeramo and Lamonaca, 2021).

Food Utilization

Reducing FLW can support the effective utilization of food by preserving its nutritional quality, safety, and edibility. Improved food handling, storage, preparation, and processing practices can minimize spoilage and contamination, thereby increasing the likelihood that nutritious food reaches consumers in an appropriate condition. Consumer education regarding food storage, preparation, food safety, and nutritional practices can further support healthier dietary choices and improve the utilization of available food resources (Santeramo and Lamonaca, 2021).

Food Stability

Reducing FLW can strengthen the resilience and stability of food systems by improving the efficiency of food production, distribution, and consumption. More efficient food systems may be better positioned to respond to disruptions associated with climate change, supply-chain interruptions, market instability, and fluctuations in food prices. Consequently, FLW reduction can contribute to the long-term sustainability and resilience of food systems and support more stable access to adequate food over time (Munang *et al.* 2011).

Integrating Food Waste Reduction into Sustainable Food Systems

In the context of growing environmental challenges, social inequalities, and economic pressures, food waste reduction and the development of sustainable food systems have received increasing global attention. Addressing food waste is essential not only for conserving natural resources but also for strengthening the resilience, efficiency, and equity of food systems. A sustainable food system is one that ensures food security and adequate nutrition for present and future populations while maintaining environmental integrity, economic viability, and social equity (Capone *et al.*, 2014).

Sustainable food systems encompass the entire food value chain, including food production, processing, distribution, consumption, and waste management. Their development is guided by principles that emphasize environmental sustainability, efficient and responsible resource utilization, economic viability, and social justice. Integrating food-waste reduction strategies throughout these interconnected stages can improve resource efficiency, minimize environmental pressures, and contribute to the development of more resilient and sustainable food systems (Van Berkum *et al.*, 2018).

Ecological Dimensions of Sustainable Food Systems

Ecological sustainability emphasizes the need to minimize the adverse environmental impacts associated with food production and consumption, including pollution, habitat degradation, biodiversity loss, and greenhouse gas emissions that contribute to climate change (Munang *et al.*, 2011).

Promoting sustainable agricultural practices, such as crop rotation, organic farming, and the judicious use of pesticides, can improve soil quality, enhance ecosystem health, and support the conservation of agricultural biodiversity. These practices also contribute to the long-term sustainability and resilience of food production systems by maintaining essential ecological processes and reducing environmental pressures (Gomiero *et al.*, 2011; Tahat *et al.*, 2020).

Economic Efficiency and Sustainability in Food Systems

Economic viability emphasizes the need to ensure that food production, processing, and distribution systems remain financially sustainable while providing equitable opportunities and benefits to the various stakeholders involved in the food supply chain (Oliver *et al.*, 2018).

Economic incentives can stimulate technological innovation, improve resource utilization, and enhance operational efficiency across food systems. However, an excessive emphasis on short-term profitability may also encourage practices such as overproduction and dependence on monoculture systems, potentially creating adverse ecological consequences. Therefore, maintaining an appropriate balance between economic profitability and environmental sustainability is essential for developing resilient, efficient, and sustainable food systems (Agarwala *et al.*, 2022; Oliver *et al.*, 2018).

Promoting Social Equity through Sustainable Food Systems

Social equity emphasizes the importance of ensuring equitable access to safe, nutritious, and affordable food while promoting fair and inclusive labour practices throughout the food supply chain. It encompasses the equitable distribution of food resources and opportunities, as well as the protection of the rights and well-being of individuals engaged in food production, processing, distribution, and related activities (Onyeaka *et al.*, 2024).

Conclusion

Food loss and food waste (FLW) are major challenges to the sustainability and efficiency of global food systems. Food losses mainly occur during production, post-harvest handling, storage, processing, and distribution, while food waste is largely associated with retail and household practices. Both result in the inefficient use of food and valuable resources such as water, land, energy, and labour. FLW has significant environmental, economic, social, and public health consequences. It contributes to greenhouse gas emissions, resource depletion, pollution, biodiversity loss, and economic losses, while also reducing opportunities to improve food access among food-insecure populations. Reducing FLW can conserve natural resources, lower environmental pressures, and improve the availability and accessibility of nutritious food.

Effective FLW reduction requires improvements in storage, transportation, processing, food recovery, supply-chain management, and consumer practices. Such measures can enhance resource efficiency and strengthen the four dimensions of food security: availability, access, utilization, and stability. Overall, reducing FLW requires coordinated action by producers, businesses, governments, communities, and consumers. Integrating FLW reduction into sustainable food systems can support environmental protection, economic efficiency, social equity, food security, and improved nutrition. Therefore, effective management and reduction of FLW are essential for developing resilient, sustainable, and equitable food systems for present and future generations.

References

1. Agarwala, C., Jemaneh, J., & Kassie, Y. (2022). Government policies and sustainable food systems: Navigating challenges, seizing opportunities, and advancing environmental and social resilience. *Law Econ*, 16(2), 88–102. <https://doi.org/10.35335/laweco.v16i2.53>

2. Australian Institute of Health and Welfare. (2020). *Australian bushfires 2019–20: Exploring the short-term health impacts*. Australian Government.
3. Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Pegenaute, F., Herrmann, F. R., Robine, J. M., Basagaña, X., Tonne, C., Antó, J. M., & Achebak, H. (2023). Heat-related mortality in Europe during the summer of 2022. *Nature Medicine*, 29, 1857–1866.
4. Berry, E. M. (2020). Food insecurity, social inequity, and sustainability. *World Review of Nutrition and Dietetics*, 121, 95–104. <https://doi.org/10.1159/000507489>
5. Bhatt, R. P. (2023). SDGs have achieved global biodiversity conservation and reduced greenhouse gas emissions by using green energy and maintaining forest cover. *GSC Advanced Research and Reviews*, 17(3), 1–21.
6. British Columbia Coroners Service. (2022). *Extreme heat and human mortality: A review of heat-related deaths in B.C. in summer 2021*. Government of British Columbia.
7. Fami, H. S., Aramyan, L. H., Sijtsema, S. J., & Alambaigi, A. (2019). Determinants of household food waste behaviour in Tehran city: A structural model. *Resources, Conservation and Recycling*, 143, 154–166. <https://doi.org/10.1016/j.resconrec.2018.12.033>
8. Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Environmental impact of different agricultural management practices: Conventional vs. organic agriculture. *Critical Reviews in Plant Sciences*, 30(2), 95–124. <https://doi.org/10.1080/07352689.2011.554355>
9. Goswami, D. (2022). *Reducing food waste: An investigation of the food waste literacy of Year 7 students in a New Zealand school* [Doctoral dissertation, The University of Waikato].
10. Graham-Rowe, E., Jessop, D. C., & Sparks, P. (2014). Identifying motivations and barriers to minimising household food waste. *Resources, Conservation and Recycling*, 84, 15–23. <https://doi.org/10.1016/j.resconrec.2013.12.005>
11. Hebrok, M., & Boks, C. (2017). Household food waste: Drivers and potential intervention points for design—an extensive review. *Journal of Cleaner Production*, 151, 380–392. <https://doi.org/10.1016/j.jclepro.2017.03.069>
12. Henderson, S. B., McLean, K. E., Lee, M. J., & Kosatsky, T. (2022). Analysis of community deaths during the catastrophic 2021 heat dome: Early evidence to inform the public health response during subsequent events in greater Vancouver, Canada. *Environmental Epidemiology*, 6(1).
13. Hickey, M. E., & Ozbay, G. (2014). Food waste in the United States: A contributing factor toward environmental instability. *Frontiers in Environmental Science*, 2, 51–78. <https://doi.org/10.3389/fenvs.2014.00051>

14. Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Summary for policymakers*. IPCC.
15. Liegeard, J., & Manning, L. (2020). Use of intelligent applications to reduce household food waste. *Critical Reviews in Food Science and Nutrition*, 60(6), 1048–1061. <https://doi.org/10.1080/10408398.2018.1556580>
16. Lin, C. S. K., Pfaltzgraff, L. A., Herrero-Davila, L., Mubofu, E. B., Abderrahim, S., Clark, J. H., Koutinas, A. A., Kopsahelis, N., Stamatelatos, K., Dickson, F., Thankappan, S., Mohamed, Z., Brocklesby, R., & Luque, R. (2013). Food waste as a valuable resource for the production of chemicals, materials and fuels: Current situation and global perspective. *Energy & Environmental Science*, 6(2), 426–464. <https://doi.org/10.1039/C2EE23440H>
17. Luo, N., Olsen, T., Liu, Y., & Zhang, A. (2022). Reducing food loss and waste in supply chain operations. *Transportation Research Part E: Logistics and Transportation Review*, 162, 102730. <https://doi.org/10.1016/j.tre.2022.102730>
18. Makate, C., Makate, M., Mango, N., & Siziba, S. (2019). Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations: Lessons from Southern Africa. *Journal of Environmental Management*, 231, 858–868. <https://doi.org/10.1016/j.jenvman.2018.10.069>
19. Mesterházy, A., Oláh, J., & Popp, J. (2020). Losses in the grain supply chain: Causes and solutions. *Sustainability*, 12(6), 2342. <https://doi.org/10.3390/su12062342>
20. Munang, R. T., Thiaw, I., & Rivington, M. (2011). Ecosystem management: Tomorrow's approach to enhancing food security under a changing climate. *Sustainability*, 3(7), 937–954. <https://doi.org/10.3390/su3070937>
21. Nénert, C., González, D. G., Giner, C., Gay, S. H., & Elasri, A. (2025). *The potential effects of reducing food loss and waste: Impacts on the triple challenge and cost-benefits analysis*. OECD Food, Agriculture and Fisheries Papers. <https://doi.org/10.1787/bd2aedc6-en>
22. Onyeaka, H., Siyanbola, K. F., Akinsemolu, A. A., Tamasiga, P., Mbaeyi-Nwaoha, I. E., Okonkwo, C. E., Odeyemi, O. A., Oladipo, E. K., *et al.* (2024). Promoting equity and justice: Harnessing the right to food for Africa's food security. *Agriculture & Food Security*, 13, 52–55. <https://doi.org/10.1186/s40066-024-00505-0>
23. Pérez-Escamilla, R. (2017). Food security and the 2015–2030 Sustainable Development Goals: From human to planetary health. *Current Developments in Nutrition*, 1(7), 5–13. <https://doi.org/10.3945/cdn.117.000513>
24. Rijkswaterstaat. (n.d.). *Room for the River*. Government of the Netherlands.
25. Santeramo, F. G., & Lamonaca, E. (2021). Food loss–food waste–food security: A new research agenda. *Sustainability*, 13(9), 4642. <https://doi.org/10.3390/su13094642>

26. Sharma, P., Bano, A., Singh, S. P., Varjani, S., & Tong, Y. W. (2024). Sustainable organic waste management and future directions for environmental protection and techno-economic perspectives. *Current Pollution Reports*, 10(3), 459–477. <https://doi.org/10.1007/s40726-024-00317-7>
27. Shen, G., Li, Z., Hong, T., Ru, X., Wang, K., Gu, Y., Han, J., & Guo, Y. (2024). The status of the global food waste mitigation policies: Experience and inspiration for China. *Environment, Development and Sustainability*, 26(4), 8329–8357. <https://doi.org/10.1007/s10668-023-03132-0>
28. Soma, T., Li, B., & Maclaren, V. (2020). Food waste reduction: A test of three consumer awareness interventions. *Sustainability*, 12(3), 907. <https://doi.org/10.3390/su12030907>
29. Stathers, T., & Mvumi, B. (2020). Challenges and initiatives in reducing postharvest food losses and food waste: Sub-Saharan Africa. In *Preventing food losses and waste to achieve food security and sustainability*. Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2019.0053.31>
30. Tahat, M., Alananbeh, K., Othman, Y., & Leskovar, D. (2020). Soil health and sustainable agriculture. *Sustainability*, 12(12), 4859. <https://doi.org/10.3390/su12124859>
31. Urugo, M. M., Tekla, T. A., Gemedie, H. F., Mersha, S., Tessema, A., Woldemichael Woldemariam, H., & Admassu, H. (2024). A comprehensive review of current approaches on food waste reduction strategies. *Comprehensive Reviews in Food Science and Food Safety*, 23(5). <https://doi.org/10.1111/1541-4337.70011>
32. World Health Organization. (2022). *Review of IPCC evidence 2022: Climate change, health and well-being*. WHO.
33. World Health Organization. (2024). *Climate change and health: World Health Assembly Resolution WHA77.14*. WHO.
34. World Health Organization. (n.d.). *Climate change*. WHO.
35. Wright, K. R. (2022). *The relationship between psychosocial factors and food waste-related behaviors among college students* [Doctoral dissertation, University of Arkansas].
36. Aziz, H. A., Rosli, N. A., & Hung, Y. T. (2020). Landfill methane emissions. In *Handbook of environment and waste management: Acid rain and greenhouse gas pollution control* (pp. 397–454). World Scientific. https://doi.org/10.1142/9789811207136_0011
37. Hariram, N. P., Mekha, K. B., Suganthan, V., & Sudhakar, K. (2023). Sustainalism: An integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability*, 15(13), 10682. <https://doi.org/10.3390/su151310682>

EVOLUTIONARY TRAJECTORIES OF ANTIMICROBIAL RESISTANCE FROM SELECTION TO DISSEMINATION: A ONE HEALTH CONTINUUM

Gundavarapu Bhargavi

Corresponding author E-mail: gbksree3@gmail.com

Abstract

Antimicrobial resistance (AMR) occurs when microorganisms, including bacteria, fungi, viruses and parasites no longer respond to antimicrobial medicines, making infections difficult or sometimes impossible to treat. AMR is a global challenge that is not just confined to the health sector; instead, it is understood as the dynamic evolutionary process that is occurring across the interconnected ecological and biological systems. AMR evolution begins with the antimicrobial exposure and selection, followed by resistance acquisition, adaptation, persistence and dissemination across the human-animal-food-environmental chain. In contrast, different evolutionary routes like combinations of chromosomal mutations, mobile genetic elements, clonal expansion and ecological persistence can also lead to clinically important MDR or XDR infections. The chapter integrates molecular evolutionary events, ecological processes, pathogen adaptation mechanisms, dissemination, and intervention, identifying opportunities along the AMR trajectory for evolution-informed surveillance, environmental management, infection prevention, and integrated One Health action. As AMR continues to pose a worldwide health challenge, accurate detection alone is not enough. Understanding how resistance evolves, persists, and spreads is the key for identifying points where its progression can be interrupted.

Keywords: Antimicrobial Resistance (AMR), Persistence, Mobile Genetic Elements, Clonal Expansion, MDR, XDR, Evolutionary Trajectory, One Health.

1. Antimicrobial Resistance as an Evolutionary and One Health Challenge

In evolutionary terms, antimicrobial resistance (AMR) is a dynamic process influenced by antimicrobial exposure, genetic variation, microbial adaptation, and ecological connectivity. In the present-day scenario, AMR should be studied beyond clinical settings, involving interconnected human, animal, food, and environmental compartments. Through these non-clinical compartments, antimicrobial residues, resistant organisms, and resistance determinants circulate. Resistance in microbes is the result of pre-existing genetic diversity, spontaneous mutations, and acquisition of resistance genes via horizontal gene transfer (HGT). Then, exposure to antimicrobials exerts an initial selective pressure that supports the emergence of resistant variants which has compromised fitness landscapes (Hughes and Andersson, 2017).

The figure 1 depicts antimicrobial resistance (AMR) as an evolving process that spans linked human, animal, food-system and environmental domains. The process starts with exposure to

and selection by antimicrobials, leading to genetic changes or uptake, followed by genetic amplification, adaptation with fitness compensation, persistence, spread and transmission, and ultimately the establishment of resistant or multidrug-resistant (MDR/XDR) populations. At every stage, evolutionary processes engage with ecological conditions and opportunities for transmission, and renewed antimicrobial selection can further strengthen resistance. The figure identifies key opportunities for intervention along the pathway, such as antimicrobial stewardship, infection prevention and control, environmental management, surveillance, diagnostic-guided treatment, and integrated One Health approaches. The key intervention principles emphasise targeting the appropriate stage of the evolutionary trajectory, applying a One Health approach, acting early, combining interventions, and focusing on evolutionary potential to limit the emergence, persistence, and dissemination of AMR.

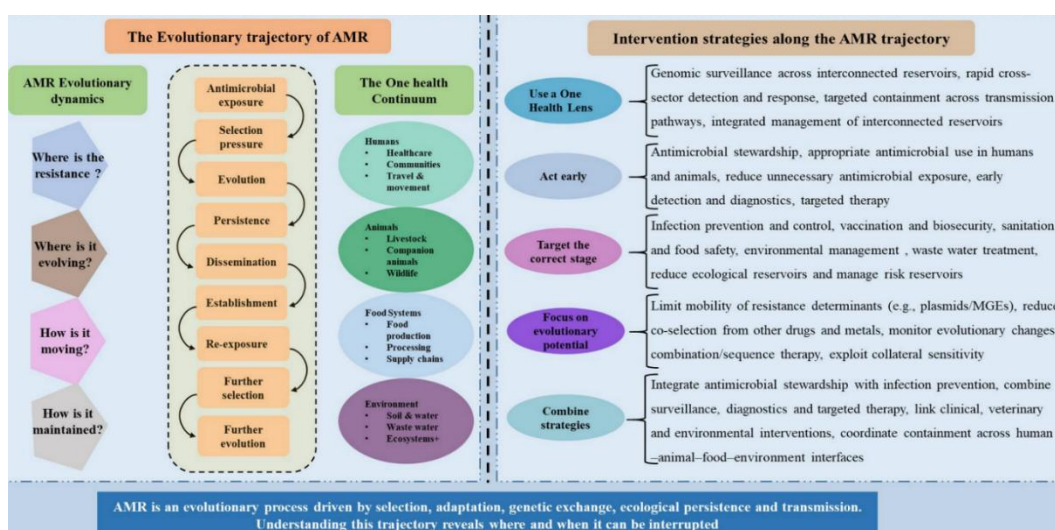


Figure 1: From selection to dissemination: evolutionary trajectories of antimicrobial resistance across the One Health continuum

Factors like sub-inhibitory antimicrobial concentrations and varying exposure levels may affect the development of resistance by altering the bacterial physiology and genetic exchange, (Andersson and Hughes, 2014; Sandegren, 2014;). Although resistance may initially impose to reduced bacterial fitness, compensatory evolution can lessen these costs and allow resistant strains to persist even when antimicrobial pressure decreases (Andersson and Hughes, 2010; Hughes and Andersson, 2017). AMR evolution therefore reflects the interaction of selection, genetic change, adaptation, persistence, population dynamics and ecological context, providing the basis for a One Health continuum from resistance emergence to dissemination and identifying opportunities for intervention along this trajectory (Fig. 1). This chapter approaches AMR through this evolutionary trajectory rather than treating molecular, clinical, ecological, and One Health dimensions as separate processes.

2. Mechanisms Driving the Evolutionary Trajectories of AMR

Bacterial resistance can arise via chromosomal mutations, gene amplification, genome plasticity, and horizontal gene transfer (HGT), which modify antimicrobial targets, regulatory mechanisms, efflux pumps, membrane permeability, or other cellular processes, ultimately diminishing drug effectiveness (MacLean *et al.*, 2010). Repeated antimicrobial exposure leads to build-up of resistance-related mutations that results in gradual enhancement of resistance, while compensatory evolution can mitigate the fitness costs and enable sustained survival (Toprak *et al.*, 2012; Andersson & Hughes, 2010). In addition, gene amplification i.e., increase in copy number and expression of genes provides an extra pathway for the development of AMR in response to environmental conditions (Sandegren & Andersson, 2009; Silva & Khare, 2024). Genome plasticity and mobile genetic elements - including plasmids, integrons, transposons, insertion sequences, and bacteriophages further facilitate the mobilisation and rearrangement of resistance determinants (Morshed, 2024; Verma *et al.*, 2019). HGT via conjugation, transformation, and transduction allows these genetic determinants to spread among bacterial populations through direct cell contact, absorption of free DNA, or transfer mediated by bacteriophages, thereby speeding up the gain and build-up of resistance traits and promoting multidrug-resistant phenotypes (von Wintersdorff *et al.*, 2016; Partridge *et al.*, 2018; Liu *et al.*, 2022; Castañeda-Barba *et al.*, 2024).

The build-up of several resistance determinants can result in the evolutionary stabilization of multidrug resistance, especially when these genes are closely linked genetically or subjected to similar selective forces. In addition to antibiotics, heavy metals, biocides and other environmental contaminants can co-select for resistance, especially when resistance determinants are physically linked to mobile genetic elements or when common cellular mechanisms provide resistance to multiple agents (Murray *et al.*, 2024). Consequently, resistance mechanisms may function either in sequence or simultaneously; for instance, chromosomal mutations occurring in strains harbouring plasmids, mobile genetic elements introducing multiple resistance genes, gene amplification increasing the expression of resistance genes, and compensatory evolution reducing fitness costs to improve persistence (Sandegren & Andersson, 2009; Andersson & Hughes, 2010; Silva & Khare, 2024; Castañeda-Barba *et al.*, 2024). Thus, the development of multi drug resistance is not the result of one mechanism alone but emerges from the interaction of genetic, population, and ecological factors that strengthen resistance in successful bacterial strains and allow its persistence and dissemination across linked One Health areas (Castañeda-Barba *et al.*, 2024; Murray *et al.*, 2024).

From resistance acquisition to clinically relevant phenotypes. The examples in the below table demonstrate that resistance among different pathogens can emerge through markedly different evolutionary pathways. For example: Pathogens like, *E. coli* (Castañeda-Barba *et al.*, 2024) and

K. pneumoniae (Yang *et al.*,2021) acquire resistance through plasmid-associated horizontal gene transfer (HGT); Methicillin-resistant *Staphylococcus aureus* (MRSA) (Lakhundi and Zhang, 2018) through acquisition of mobile genetic elements followed by clonal selection; *A. baumannii* (Lucidi *et al.*,2024) highlights the interaction of selection, adaptation and healthcare persistence; and *M. tuberculosis* (Emane *et al.*,2021)illustrates a predominantly stepwise chromosomal pathway.

Table 1: Evolutionary trajectories of major AMR pathogens:

Pathogen	Dominant evolutionary route	Key resistance mechanisms and evolutionary features	Ecological context	Evolutionary trajectory
<i>Escherichia coli</i>	Horizontal gene transfer (HGT) and clonal expansion	Plasmid-mediated ESBL determinants, particularly <i>bla</i> CTX-M; plasmid stabilization, genetic exchange & clonal expansion.	Human, animal, food, and environmental compartments, including wastewater and food-producing animals.	Antimicrobial selection → acquisition of resistance determinants → plasmid stabilization → clonal expansion and/or HGT → movement across One Health compartments → clinical establishment.
<i>Klebsiella pneumoniae</i>	HGT and clonal expansion	Carbapenemase-associated plasmids and their rearrangement, recombination, and accumulation of resistance determinants; convergence of resistance and virulence-associated traits.	Healthcare settings and interconnected ecological reservoirs.	Horizontal acquisition → plasmid evolution and rearrangement → multidrug resistance → clonal expansion → resistance-virulence convergence → dissemination.

<i>Staphylococcus aureus</i>	Mobile genetic element acquisition and clonal evolution	Acquisition of SCCmec carrying <i>mecA</i> , encoding PBP2a; selection of successful genetic backgrounds and subsequent accumulation of additional resistance.	Healthcare and community settings.	Susceptible lineage → SCCmec acquisition → β -lactam resistance → selection of successful genetic backgrounds → clonal expansion → ecological adaptation → additional resistance.
<i>Acinetobacter baumannii</i>	Antimicrobial selection, adaptation, genomic Plasticity and HGT	Acquired and adaptive resistance mechanisms involving antimicrobial targets, permeability, efflux, and resistance determinants; environmental persistence and genomic plasticity.	Antimicrobial-rich healthcare environments, particularly hospitals and intensive-care settings.	Environmental persistence → healthcare-associated niche → antimicrobial selection → resistance acquisition/selection → adaptation and persistence → clonal expansion and transmission.
<i>Mycobacterium tuberculosis</i>	Chromosomal mutation and stepwise selection	Predominantly chromosomal resistance mutations, sequential mutation accumulation, compensatory evolution, and adaptation during infection.	Within-host environments and population-level transmission.	Within-host variation → antimicrobial selection → chromosomal resistance mutation → expansion → compensatory/adaptive evolution → sequential acquisition of additional resistance → MDR/XDR tuberculosis.

3. Environmental and Ecological Fields of AMR Evolution

Environmental compartments that provide sites for selection, persistence, genetic exchange and route for dissemination of AMR contribute to its evolution. Human activities like inappropriate discharge of wastewater, antimicrobial use, manure application in agriculture and irrigation can contribute to the accumulation of antimicrobial residues, resistant bacteria, and resistance genes, altering environmental resistomes, and thus, linking human, animal, food, and environmental systems (Larsson and Flach, 2022; Murray *et al.*, 2024). However, factors like persistence, transferability, functional expression, and ecological connectivity influence the evolutionary potential of AMR. Therefore, environmental AMR should be considered in relation to the ecological conditions that enable resistance to evolve, persist, transfer, and disseminate across the One Health continuum (Larsson and Flach, 2022; WHO, 2024).

4. The Concept of Connectivity is Crucial to Understanding the Rise of Pathogens

Rather than understanding AMR as a simple linear progression, it should be viewed as the dynamic process as it involves the movement of resistance determinants through various host and environmental settings before integrating into transmissible strains (Larsson and Flach, 2022; Castañeda-Barba *et al.*, 2024). One Health connectivity means more than just the possibility of exchange; it determines whether resistance can spread, remain present, and eventually take hold in clinically significant pathogens. Mutation results in genetic variation, while selection enriches the resistant varieties; whereas horizontal gene transfer and mobile genetic elements enable the movement of genetic material across bacterial populations and ecological boundaries (Jallow *et al.*, 2026; Arnold *et al.*, 2022; Castañeda-Barba *et al.*, 2024). Thus, interconnected systems involving humans, animals, food, and the environment can provide opportunities for the persistence, spread, and eventual emergence of clinically significant resistant pathogens (Debergh, 2024; Larsson and Flach, 2022).

5. Interrupting the Evolutionary Path of AMR

Viewing AMR as an evolutionary process shifts the focus from elimination of resistance once it emerges to interruption of its development at several points along the way. Antimicrobial stewardship can reduce selective pressure. Infection prevention, vaccination, sanitation, food safety, veterinary practices, and environmental management can help reduce persistence and transmission across the interconnected One Health domains (WHO, 2026; WHO, 2024). Surveillance can be an early-warning evolutionary system by combining resistance trends with genomic, resistome, antimicrobial-use and ecological data (WHO, 2026). Therefore, effective control of antimicrobial resistance requires concerted actions across the One Health framework, from reducing selective pressure and hindering resistance development to limiting genetic transfer, preventing long-term survival, stopping spread and monitoring evolutionary changes.

6. Future Perspectives: From AMR Surveillance to Evolutionary Prediction

A major future priority in AMR management will be to shift the focus from retrospective resistance detection to evolutionary prediction. Resistance prevalence indicates the current status of a population but does not necessarily reflect the future direction of that population; the combination of whole-genome sequencing, metagenomics, resistome profiling, long-read sequencing, data on antimicrobial use, environmental measurements and epidemiological data may provide information on the resistance determinants that are increasing in prevalence, acquiring mobility or entering successful bacterial lineages. Future surveillance to improve AMR containment should take into account its evolutionary potential, such as genomic context, mobility, host range, fitness costs, compensatory adaptation and selective pressures. Combining genomic, ecological and epidemiological datasets could reveal insights into controlling AMR that are often obscured by the independent studies.

However, genetic similarity alone cannot be used to establish direct transmission and environmental detection of a resistance determinant. Here, environmental surveillance may thus act as an early-warning interface linking antimicrobial residues, resistant organisms, resistance genes, mobile genetic elements and microbial community dynamics across interconnected systems. These surveillance tools should be incorporated into an evolutionary framework based on One Health to understand how selection and genetic changes in one domain might influence resistance patterns in other domains.

Future management of AMR must consider evolutionary trade-offs such as fitness costs, compensatory adaptation and collateral sensitivity, as well as bacterial population size, genetic context, microbial interactions, host influences and exposure to treatments. Grasping the interactions between these stages can help us to design specific measures for the containment of AMR. The future of AMR surveillance should also include identifying where it is evolving, how it is maintained, and where the trajectory can be interrupted.

Conclusion

AMR is an ongoing evolutionary process resulting from the interaction of antimicrobial selection pressures on microbes, their genetic makeup, how well they adapt to their environment (e.g., in a hospital), and how easily they are transmitted from one host to another. Resistance can arise through mutations or by acquiring genes that confer resistance; once resistance arises, it may persist in a population of microbes and be passed down through generations. Finally, resistance can spread through various interconnected human, animal, food, and environmental systems. The perspective of AMR as an evolutionary trajectory within the One Health continuum offers a means to link the molecular basis for resistance with the ecological and epidemiological dynamics that govern its emergence, persistence, and dissemination. Therefore, this perspective allows us to shift AMR control efforts away from dealing with existing resistance toward

preventing and disrupting resistance emergence, persistence, and transmission. Integrating evolutionary biology with genomics, microbiology, ecology, clinical practice, and One Health surveillance will be necessary to identify evolving resistance trajectories at an early stage and deploy countermeasures against them prior to their establishment.

References

1. Andersson, D. I., & Hughes, D. (2010). Antibiotic resistance and its cost: Is it possible to reverse resistance? *Nature Reviews Microbiology*, 8(4), 260–271.
2. Andersson, D. I., & Hughes, D. (2014). Microbiological effects of sublethal levels of antibiotics. *Nature Reviews Microbiology*, 12(7), 465–478.
3. Arnold, B. J., Huang, I. T., & Hanage, W. P. (2022). Horizontal gene transfer and adaptive evolution in bacteria. *Nature Reviews Microbiology*, 20(4), 206–218.
4. Castañeda-Barba, S., Top, E. M., & Stalder, T. (2024). Plasmids, a molecular cornerstone of antimicrobial resistance in the One Health era. *Nature Reviews Microbiology*, 22(1), 18–32.
5. Debergh, H. (2024). *Investigation of resistance mechanisms and their transmission in emerging pathogens applying the «one health» approach* [Doctoral dissertation, Université de Liège].
6. Emame, A. K. A., Guo, X., Takiff, H. E., & Liu, S. (2021). Drug resistance, fitness and compensatory mutations in *Mycobacterium tuberculosis*. *Tuberculosis*, 129, 102091.
7. Hughes, D., & Andersson, D. I. (2017). Evolutionary trajectories to antibiotic resistance. *Annual Review of Microbiology*, 71, 579–596.
8. Jallow, L., Bojang, A., & Bajinka, O. (2026). Conjugation as an evolutionary bottleneck in antimicrobial resistance spread. *Frontiers in Microbiology*, 17, 1863866.
9. Lakhundi, S., & Zhang, K. (2018). Methicillin-resistant *Staphylococcus aureus*: Molecular characterization, evolution, and epidemiology. *Clinical Microbiology Reviews*, 31(4). <https://doi.org/10.1128/CMR.00020-18>
10. Larsson, D. J., & Flach, C. F. (2022). Antibiotic resistance in the environment. *Nature Reviews Microbiology*, 20(5), 257–269.
11. Liu, G., Thomsen, L. E., & Olsen, J. E. (2022). Antimicrobial-induced horizontal transfer of antimicrobial resistance genes in bacteria: A mini-review. *Journal of Antimicrobial Chemotherapy*, 77(3), 556–567.
12. Lucidi, M., Visaggio, D., Migliaccio, A., Capecchi, G., Visca, P., Imperi, F., & Zarrilli, R. (2024). Pathogenicity and virulence of *Acinetobacter baumannii*: Factors contributing to the fitness in healthcare settings and the infected host. *Virulence*, 15(1), 2289769.
13. MacLean, R. C., Hall, A. R., Perron, G. G., & Buckling, A. (2010). The population genetics of antibiotic resistance: Integrating molecular mechanisms and treatment contexts. *Nature Reviews Genetics*, 11(6), 405–414.

14. Morshed, S. (2024). Hospital wastewater as a reservoir of antimicrobial resistance genes: Implications for public health and genomic surveillance in the United States. *Review of Applied Science and Technology*, 3(4), 448–508.
15. Murray, L. M., Hayes, A., Snape, J., Kasprzyk-Hordern, B., Gaze, W. H., & Murray, A. K. (2024). Co-selection for antibiotic resistance by environmental contaminants. *npj Antimicrobials and Resistance*, 2(1), 9.
16. Partridge, S. R., Kwong, S. M., Firth, N., & Jensen, S. O. (2018). Mobile genetic elements associated with antimicrobial resistance. *Clinical Microbiology Reviews*, 31(4). <https://doi.org/10.1128/CMR.00088-17>
17. Sandegren, L. (2014). Selection of antibiotic resistance at very low antibiotic concentrations. *Uppsala Journal of Medical Sciences*, 119(2), 103–107.
18. Sandegren, L., & Andersson, D. I. (2009). Bacterial gene amplification: Implications for the evolution of antibiotic resistance. *Nature Reviews Microbiology*, 7(8), 578–588.
19. Silva, K. P. T., & Khare, A. (2024). Antibiotic resistance mediated by gene amplifications. *npj Antimicrobials and Resistance*, 2(1), 35.
20. Toprak, E., Veres, A., Michel, J. B., Chait, R., Hartl, D. L., & Kishony, R. (2012). Evolutionary paths to antibiotic resistance under dynamically sustained drug selection. *Nature Genetics*, 44(1), 101–105.
21. Verma, J., Bag, S., Saha, B., Kumar, P., Ghosh, T. S., Dayal, M., ... & Das, B. (2019). Genomic plasticity associated with antimicrobial resistance in *Vibrio cholerae*. *Proceedings of the National Academy of Sciences*, 116(13), 6226–6231.
22. Von Wintersdorff, C. J., Penders, J., Van Niekerk, J. M., Mills, N. D., Majumder, S., Van Alphen, L. B., ... & Wolffs, P. F. (2016). Dissemination of antimicrobial resistance in microbial ecosystems through horizontal gene transfer. *Frontiers in Microbiology*, 7, 173.
23. World Health Organization. (2024). *Action against antimicrobial resistance requires a One Health approach*. WHO Regional Office for Europe. <https://link.springer.com/article/10.1186/s44149-025-00210-w>
24. World Health Organization. (2026). *The global action plan on antimicrobial resistance 2026–2036*. World Health Organization. <https://www.who.int/news/item/25-05-2026-the-world-health-assembly-adopts-updated-global-action-plan-on-antimicrobial-resistance-%282026-2036%29>
25. Yang, X., Dong, N., Chan, E. W. C., Zhang, R., & Chen, S. (2021). Carbapenem resistance-encoding and virulence-encoding conjugative plasmids in *Klebsiella pneumoniae*. *Trends in Microbiology*, 29(1), 65–83.

PROBIOTICS AND TRADITIONAL FERMENTED FOODS: MICROBIAL ALLIES FOR GUT AND METABOLIC HEALTH

K. Sunita Raju

Mahrajah's College (Autonomous), Vizianagaram, Andhra Pradesh, India

Corresponding author E-mail: ksunitaraju@gmail.com

Abstract

India has a rich diversity of traditional fermented foods that reflect regional food habits, indigenous knowledge, and cultural heritage. These traditional foods are typically produced through spontaneous fermentation, a natural process driven by diverse microbial communities comprising bacteria, yeasts, and molds. Across different regions of India, fermented products such as idli, dosa, dhokla, dahi, kinema, gundruk, sinki, sidra, and fermented bamboo shoots represent an integral part of indigenous food systems. Beyond their cultural significance, these foods play a crucial role in enhancing nutritional security, extending shelf life, improving sensory attributes, and promoting human health through probiotic and functional benefits. Recent advancements in molecular characterization techniques and metagenomic analyses have provided deeper insights into the complex microbial ecosystems associated with traditional fermented foods. These studies have identified a wide range of beneficial microorganisms, particularly lactic acid bacteria, *Bacillus* species, and various yeast strains, which play a vital role in enhancing the nutritional value, safety, sensory characteristics, and functional properties of these foods (Samantaray & Saha, 2026).

Keywords: Traditional Fermented Foods, Microbial Communities, Probiotics, Beneficial Microorganisms.

1. Introduction

Long before the word “probiotic” entered the scientific vocabulary, communities across the world had already learned, through generations of trial and observation that fermented foods kept people healthy. Milk turned into curd lasted longer and sat easier on the stomach; batters left to sour overnight rose better and were gentler to digest; vegetables packed in brine survived the lean months and seemed to ward off illness. What was once explained through custom and taste is now understood through microbiology: fermentation is, in large part, a story of beneficial microorganisms transforming raw ingredients and, in the process, endowing food with living cultures capable of promoting human health (Patel *et al.*, 2021).

This chapter examines probiotics as both a scientific concept and a lived tradition. It draws on the growing body of research on India's traditional fermented foods — idli, dosa, dhokla, dahi, lassi, kinema, gundruk, sinki, ngari, and fermented bamboo shoots, among many others — to illustrate how indigenous food systems have functioned, unknowingly but effectively, as

reservoirs of probiotic microorganisms (Sarma & Gupta, 2022). It then situates these traditional practices within the broader scientific framework of probiotic definition, mechanism, and health benefit, before turning to the challenges of standardization and safety, and the opportunities that modern omics technologies now offer for validating and scaling up what indigenous knowledge has long practiced (Samantaray & Saha, 2026).

2. Defining Probiotics

Probiotics are commonly defined as live microorganisms which, when administered in adequate amounts, confer a health benefit on the host. This definition, though concise, carries several important implications. First, the organisms must be alive and present in sufficient numbers at the point of consumption; dead or denatured cultures, however beneficial their metabolites might once have been, do not meet the strict definition of a probiotic. Second, the benefit must be demonstrable rather than assumed a distinction that becomes especially relevant when traditional foods, rich in indigenous microbial communities, are evaluated against the same scientific standard applied to commercial probiotic supplements.

Most organisms recognized as probiotics belong to the lactic acid bacteria (LAB) group, particularly the genera *Lactobacillus*, *Lactococcus*, *Leuconostoc*, and *Pediococcus*, along with certain yeasts such as *Saccharomyces* species. These organisms share a common metabolic signature: they ferment sugars into organic acids chiefly lactic acid lowering the pH of their environment and, in doing so, both preserving the food and creating conditions unfavorable to spoilage and pathogenic microbes (Bhattacharya *et al.*, 2022).

What distinguishes traditional fermented foods from many manufactured probiotic products is that the former rarely contain a single, well-characterized strain. Instead, they harbor complex and dynamic microbial consortia bacteria, yeasts, and occasionally molds that interact with one another and with the substrate over the course of fermentation. This complexity is both strengths, in terms of the diversity of metabolites and functions generated, and a challenge, in terms of standardization and safety assurance.

3. Traditional Fermented Foods as Natural Reservoirs of Probiotics

India's geographic and cultural diversity has given rise to an unusually broad repertoire of fermented foods, each shaped by locally available raw materials cereals, milk, vegetables, legumes, fish, and meat and by climate-adapted preparation methods passed down largely through oral and practical tradition rather than written protocol.

3.1 Cereal-Based Foods

Idli, dosa, appam, and dhokla batters are fermented principally by lactic acid bacteria such as *Lactobacillus fermentum* and *Leuconostoc mesenteroides*, working alongside yeasts including *Saccharomyces cerevisiae*. This bacterial-yeast partnership is responsible not only for the characteristic sourness, aeration, and texture of these foods but also for a meaningful probiotic

load consumed daily by millions of people across South and Western India, largely without any awareness that they are practicing functional nutrition (Bhattacharya *et al.*, 2022).

3.2 Milk-Based Foods

Dahi, lassi, and shrikhand are fermented by organisms such as *Lactococcus lactis*, *Streptococcus thermophilus*, and *Lactobacillus acidophilus*. These products are among the most extensively studied traditional probiotic foods in India, valued for improving lactose digestion, extending the shelf life of milk in the absence of refrigeration, and contributing beneficial organisms directly to the gut microbiota (Patel *et al.*, 2021).

3.3 Vegetable-Based Foods

In the Himalayan and northeastern regions, vegetables are preserved through natural fermentation to produce gundruk, sinki, and fermented bamboo shoots. These products are dominated by lactic acid bacteria that not only extend the shelf life of seasonal produce but also increase its nutritional value, offering rural and hill communities a probiotic-rich food source through the winter months (Sarma & Gupta, 2022).

3.4 Soybean-Based Foods

Kinema, hawaijar, and tungrymbai, widely consumed in Northeast India, are fermented predominantly by *Bacillus subtilis* and related species rather than lactic acid bacteria. These organisms secrete proteolytic enzymes that break down soybean proteins, improving digestibility and generating distinctive flavor compounds, and represent a class of probiotic-associated fermentation somewhat distinct from the LAB-dominated foods described above (Gautam *et al.*, 2026).

3.5 Fish and Meat-Based Foods

Fermented fish and meat products such as ngari, hentak, and sidra, prepared in coastal and northeastern India, involve complex bacterial and yeast communities that contribute to preservation as well as to the distinctive taste and aroma valued in regional cuisines. Though less studied from a probiotic standpoint than cereal or dairy ferments, these foods form an important part of the broader picture of India's fermented food heritage (Sarma & Gupta, 2022).

4. Microbial Diversity Underlying Probiotic Potential

The probiotic potential of traditional fermented foods rests on three broad microbial groups, each contributing distinct functional roles.

4.1 Lactic Acid Bacteria

Lactic acid bacteria are the most consistently identified probiotic candidates in Indian fermented foods, spanning cereal, dairy, and vegetable substrates. Beyond acidification, LAB produce bacteriocins, vitamins, and other bioactive compounds that enhance food safety and confer functional properties, and their probiotic activity is increasingly linked to gut health and immune regulation (Wang *et al.*, 2023).

4.2 Yeasts

Yeasts such as *Saccharomyces cerevisiae*, *Candida tropicalis*, and *Debaryomyces hansenii* contribute to leavening, mild alcohol production, and the development of aroma and flavor through volatile compounds and enzymatic activity, working in tandem with bacterial communities rather than in isolation (Samantaray & Saha, 2026).

4.3 Molds

Certain fermentations, particularly those involving soybean and some cereal substrates, rely on filamentous fungi such as *Aspergillus oryzae* and *Rhizopus oligosporus*, which secrete extracellular enzymes that break down complex carbohydrates, proteins, and lipids, improving digestibility and nutrient release even where the mold itself is not considered probiotic in the strict sense. (Xu *et al.*, 2022).

Recent metagenomic and multi-omics studies have begun to map these microbial ecosystems in far greater detail than classical culture-based methods allowed, revealing novel strains with probiotic and industrial potential and offering a scientific basis for practices that indigenous communities have refined empirically over centuries.

5. Mechanisms of Probiotic Action

Probiotic microorganisms exert their effects through several interconnected mechanisms:

Competitive exclusion and acidification: By rapidly consuming available nutrients and lowering pH through organic acid production, probiotic bacteria create an environment unfavorable to pathogenic and spoilage organisms.

Production of antimicrobial compounds: Bacteriocins and other antimicrobial metabolites directly inhibit competing microorganisms.

Enzymatic breakdown of substrates: Microbial enzymes hydrolyze proteins, carbohydrates, and anti-nutritional compounds such as phytates and tannins, improving nutrient bioavailability and digestibility.

Modulation of the gut microbiota: Regular intake of live microorganisms can shift the composition and diversity of the resident gut microbial community.

Interaction with the host immune system: Probiotic organisms and their metabolites can stimulate immune cell activity and strengthen gut barrier function.

These mechanisms operate together rather than in isolation, which is one reason why whole fermented foods with their diverse microbial and metabolite content are increasingly viewed as complementary to, rather than simply substitutable by, single-strain probiotic supplements.

6. Health Benefits of Probiotics

6.1 Digestive Health

The most consistently documented benefit of probiotic consumption is improved digestive function. Lactic acid bacteria help maintain intestinal microbial balance, enhance nutrient

absorption, and are associated with reduced incidence of constipation, diarrhea, and symptoms of irritable bowel syndrome. Fermented dairy products in particular have been shown to improve lactose digestion in individuals with reduced lactase activity (Bhattacharya *et al.*, 2022).

6.2 Immune Modulation

Probiotic microorganisms interact with gut-associated lymphoid tissue, enhancing immune cell activity, reinforcing gut barrier integrity, and potentially reducing susceptibility to infection. This immune-modulatory role is one of the more actively researched dimensions of probiotic science, with fermented foods studied as a dietary route to sustained, low-level immune support rather than an acute intervention (Wastyk *et al.*, 2021).

6.3 Metabolic Health

Bioactive compounds generated during fermentation — including short-chain fatty acids and various peptides — have been linked to anti-inflammatory effects and to improvements in blood glucose regulation, lipid metabolism, and body weight management, positioning fermented foods as a potential dietary tool in the prevention of lifestyle-related disorders such as obesity, diabetes, and cardiovascular disease (Samantaray & Saha, 2026; Xu *et al.*, 2022).

7. Challenges in Harnessing Probiotics from Traditional Foods

Despite their evident benefits, traditional fermented foods face several obstacles that limit their scientific validation and commercial scale-up as recognized probiotic sources.

Lack of standardization: Spontaneous fermentation without controlled starter cultures leads to variability in microbial composition, taste, texture, and safety from batch to batch and household to household (Ray *et al.*, 2023).

Microbial contamination risk: Preparation under non-industrial, often household, conditions increase exposure to pathogenic or spoilage organisms where hygiene practices are inconsistent (Xu *et al.*, 2022).

Limited shelf life: Many traditional products remain highly perishable due to moisture content and the absence of adequate packaging or cold-chain infrastructure (Tamang *et al.*, 2022).

Weak commercialization and regulatory documentation: Many indigenous fermented foods lack the microbial characterization, safety data, and nutritional documentation required for entry into regulated national and international markets (Gautam *et al.*, 2026).

Addressing these challenges will require coordinated investment in microbial research, the development of validated starter cultures derived from traditional isolates, improved hygiene and packaging practices, and policy frameworks that support both food safety and the preservation of indigenous fermentation knowledge.

8. Future Prospects

The convergence of traditional food knowledge with modern biotechnology offers considerable promise. Metagenomic and multi-omics approaches encompassing whole-genome sequencing,

metabolomics, and proteomics are increasingly able to identify the specific strains and metabolites responsible for the functional properties of traditional ferments, providing a scientific foundation on which standardized, safety-validated starter cultures can be built without discarding the diversity that gives these foods their character.

Such standardization, paired with improved packaging, cold-chain logistics, and deliberate branding, could allow indigenous fermented foods to move beyond local and regional consumption into recognized functional-food and nutraceutical markets, generating economic opportunity for the communities that have sustained these practices. At the same time, documentation of preparation methods and regional food cultures remains essential, both to preserve cultural heritage and to ensure that scientific advancement builds on, rather than displaces, indigenous knowledge.

Conclusion

Probiotics, as a scientific category, formalize what many traditional food cultures have long practiced through fermentation: the deliberate cultivation of beneficial microorganisms to preserve food, improve its nutritional quality, and support human health. India's traditional fermented foods spanning cereal, dairy, vegetable, soybean, fish, and meat substrates illustrate the depth and regional variety of this practice, and modern molecular tools are only now beginning to reveal the full extent of the microbial diversity involved.

Realizing the full potential of these foods as recognized, scalable sources of probiotics will depend on bridging the gap between indigenous practice and scientific validation through standardization, safety assessment, and thoughtful commercialization without eroding the traditional knowledge from which this potential originates. Understood in this way, traditional fermented foods are not simply artifacts of culinary history; they are a living, ongoing contribution to the science of probiotics and functional nutrition.

References

1. Bhattacharya, S., Das, A., Roy, D., & Singh, P. (2022). Bacterial diversity of traditional fermented food idli by high-throughput sequencing. *Journal of Food Science and Technology*, 59(4), 1452–1461.
2. Gautam, D., Sharma, R., & Devi, M. (2026). Indigenous fermented foods of Northeast India: Emerging opportunities in functional foods and microbiota-driven nutrition. *Food Bioscience*. Advance online publication.
3. Patel, A., Shah, N., & Mehta, R. (2021). Microbial diversity and functionality of traditional fermented milk products of India: Current scenario and future perspectives. *International Dairy Journal*, 114, 104941.
4. Ray, R. C., Joshi, V. K., & Tamang, J. P. (2023). Traditional fermented foods of Asia: Challenges and future opportunities. *Food Research International*, 165, 112456.

5. Samantaray, P., & Saha, S. (2026). Decoding the microbial diversity of Indian fermented foods: Integrating ethnobiology, multi-omics and functional insights. *Foods*, 15(4), 687–705.
6. Sarma, U., & Gupta, S. (2022). Ethnic fermented food and beverages of India: Interplay of microbes, immunity, and nutrition. *Nutrition and Health*, 28(3), 327–339.
7. Tamang, J. P., Cotter, P. D., Endo, A., *et al.* (2022). Fermented foods in a global age: East meets West. *Comprehensive Reviews in Food Science and Food Safety*, 21(1), 184–214.
8. Wang, Y., Zhang, C., Liu, F., Jin, Z., & Xia, X. (2023). Functional characteristics of lactic acid bacteria in fermented foods. *Critical Reviews in Food Science and Nutrition*, 63(22), 5841–5855.
9. Xu, M., Su, S., Zhang, Z., Jiang, S., Zhang, J., & Xu, Y. (2022). Benefits and risks of traditional fermented foods: A global meta-analysis. *Frontiers in Microbiology*, 13, 1045096.

INSIGHTS INTO AQUATIC FOODS AS A PATHWAY TO NUTRITION, SUSTAINABILITY AND INCLUSIVE FOOD SYSTEMS BEYOND PROTEIN SOURCE

Y. Shanti Prabha

Department of Zoology,
Government Degree College, Vizianagaram, Andhra Pradesh, India

Abstract

Aquatic foods are increasingly recognised as important components of sustainable food systems because they connect nutrition, environmental sustainability, livelihoods and social well-being. This review examines the multidimensional contribution of fish, shellfish, seaweeds and other aquatic foods to healthy and sustainable diets, with particular emphasis on nutritional value, environmental performance, livelihood security and gender inclusion. Evidence indicates that aquatic foods provide high-quality protein, essential omega-3 fatty acids and several critical micronutrients, while selected fisheries and aquaculture systems can generate comparatively lower environmental pressures than many terrestrial animal-source foods. However, sustainability outcomes vary considerably according to species, production systems, geography and governance. The review further highlights the importance of small-scale fisheries, community-based aquaculture and women's participation in aquatic-food value chains. Significant research gaps remain regarding underutilised species, affordability, climate resilience, gender equity and integrated nutrition–environment assessments. A systems-based approach is therefore essential to realise the potential of aquatic foods for healthy diets, resilient livelihoods and sustainable living.

Keywords: Aquatic Foods, Sustainable Diets, Nutrition Security, Livelihood Resilience, Women's Empowerment.

Introduction

Aquatic foods, often broadly referred to as “aqua foods,” include fish, crustaceans, molluscs, aquatic plants such as seaweeds, and other edible organisms obtained from oceans, rivers, lakes, wetlands and aquaculture systems. For centuries, these foods have formed an important component of human diets, particularly in coastal, riverine and lake-dependent communities. In the contemporary context, however, their importance extends far beyond traditional food consumption. Aqua foods are increasingly recognised as an important component of healthy diets, food and nutrition security, sustainable livelihoods, resilient food systems and environmentally responsible living. Their nutritional richness, diversity, cultural acceptability and potential to be produced through comparatively resource-efficient systems make them

particularly relevant to the search for sustainable solutions to the interconnected challenges of malnutrition, population growth, climate change and environmental degradation (FAO, 2012; FAO, 2022).

Fish and other aquatic animal foods are particularly valuable sources of high-quality proteins and essential amino acids, while also supplying important vitamins and minerals. Depending on the species, aquatic foods can provide vitamin A, vitamin D and B-group vitamins, as well as iron, zinc, calcium, iodine, selenium, phosphorus, magnesium and potassium. Fatty fish are especially notable for their content of the long-chain omega-3 polyunsaturated fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These nutrients contribute to normal physiological functioning and are particularly important in relation to cardiovascular health, neurological development and overall nutritional adequacy. FAO has highlighted that aquatic foods can provide nutrients that may be scarce in some predominantly plant-based diets, meaning that even relatively modest quantities can make meaningful contributions to dietary quality (FAO, 2022).

The significance of aqua foods becomes even greater when viewed through the concept of sustainable living. Sustainable living involves meeting present human needs while conserving the ecological, economic and social resources required by future generations. Food choices are an important component of this concept because food production influences land use, freshwater use, biodiversity, greenhouse-gas emissions, energy consumption and waste generation. FAO and WHO therefore describe sustainable healthy diets as dietary patterns that promote health and nutritional well-being while having low environmental impacts and remaining accessible, affordable, safe, equitable and culturally acceptable (FAO & WHO, 2019).

The sustainability of aquatic food systems depends on how the resources are harvested, farmed, processed, transported, marketed and consumed. Unsustainable fishing practices, habitat degradation, overfishing, excessive use of inputs, water-quality deterioration, disease outbreaks, inappropriate feed ingredients, energy-intensive production and post-harvest losses can undermine the environmental advantages associated with aquatic foods. Consequently, sustainable living requires not merely increasing aqua-food consumption, but ensuring that these foods originate from responsibly managed and environmentally sound production and supply systems.

Food loss and waste reduction is therefore an important bridge between aqua-food nutrition and sustainable living. Improving cold-chain infrastructure, hygienic handling, preservation, drying, smoking, freezing, fermentation, canning and other appropriate processing technologies can increase the availability of aquatic foods while reducing losses. Such measures are particularly important in developing regions where inadequate storage and processing facilities may prevent nutritious foods from reaching consumers. FAO also identifies improved preservation technologies, strengthened supply chains and reduced food loss and waste as important

components of nutrition-sensitive aquatic food systems. FAO has highlighted the importance of nutrition-sensitive approaches that specifically consider women and children, improved preservation technologies and stronger supply chains to realise the nutritional potential of fish and other aquatic foods (FAO, 2023).

Healthy aquatic ecosystems are essential for maintaining the long-term supply of fish, shellfish, seaweeds and other aquatic foods. Protecting aquatic biodiversity, reducing pollution, managing fisheries responsibly, improving aquaculture efficiency and minimising food losses are therefore not separate environmental objectives; they are fundamental requirements for long-term nutritional security.

Literature Review

1. Aquatic Foods within the Emerging Sustainable Food-System Framework

Aquatic foods, or “blue foods,” include finfish, crustaceans, molluscs, cephalopods, aquatic plants, seaweeds, algae and other aquatic organisms obtained through capture fisheries or aquaculture. They come from marine, coastal, freshwater and other aquatic environments. The literature increasingly treats them not simply as sources of animal protein, but as interconnected components of nutrition, environmental sustainability, livelihoods, economic development, climate resilience, biodiversity and social equity (Golden *et al.*, 2021).

A major insight is that aquatic-food diversity is itself a nutritional asset. Different species provide different combinations of calcium, iron, zinc, vitamin A, vitamin B12 and long-chain omega-3 fatty acids such as EPA and DHA. Small indigenous fish and products from small-scale fisheries can be especially valuable because they may be locally accessible and nutrient-rich even when their commercial value is low.

Aquatic foods are therefore relevant to nutrition-sensitive food systems and the “triple burden of malnutrition,” which combines undernutrition and micronutrient deficiencies with obesity and diet-related non-communicable diseases. Fish and other aquatic foods can provide highly digestible protein and micronutrients including iron, zinc, iodine, selenium, calcium and vitamin B12. Fatty fish are particularly important sources of EPA and DHA, while some species provide vitamin D and other nutrients that may be limited in predominantly plant-based diets (Golden *et al.*, 2021; FAO, 2024).

Climate change presents both risks and adaptation challenges. Warming, ocean acidification, sea-level rise, altered rainfall, extreme weather, hypoxia and eutrophication can affect production, distribution, safety and economic viability. Cao *et al.* (2023) reported that more than 90% of global blue-food production is exposed to substantial risks from human-induced environmental change. Climate resilience therefore needs to be integrated into aquatic-food planning.

Sustainability also includes livelihoods and social justice. Fisheries and aquaculture support employment and income across production, processing, trading, transport, retail and food

service, especially in rural and coastal communities. Yet environmental efficiency alone does not guarantee equitable outcomes. Secure resource access, fair markets, decent labour conditions, gender equity, affordability and participation in governance are also necessary.

Consumer access is equally important. Nutrient-rich aquatic foods cannot improve diets if they are unaffordable or unavailable. Prices, seasonality, cultural preferences, infrastructure and geographical distribution influence consumption. Supply expansion may reduce prices, but local value chains, cold storage, transportation, processing, institutional procurement and nutrition education may also be required.

2. Aquatic Foods and Healthy Diets

Aquatic foods are nutritionally diverse and should not be treated as one homogeneous category. Their nutrient composition varies with species, size, habitat, trophic position and production system. This diversity creates opportunities to improve diet quality, particularly where diets rely heavily on staple cereals and provide insufficient micronutrients (Golden *et al.*, 2021; Farmery *et al.*, 2021; Koehn *et al.*, 2023).

Species-level diversity matters. Small indigenous fish consumed whole may provide substantial calcium and other micronutrients; larger fatty fish can supply EPA and DHA; bivalves can provide iron and vitamin B12; and seaweeds can contribute iodine, minerals, dietary fibre and bioactive compounds. Dietary strategies should therefore consider which aquatic foods are available, affordable, culturally acceptable and nutritionally appropriate rather than simply recommending “more fish.”

Aquatic foods can help address hidden hunger and micronutrient deficiencies, especially when locally available through small-scale fisheries, inland fisheries, household ponds or community aquaculture. They may also support maternal and child nutrition because pregnancy and childhood require adequate protein, iron, zinc, iodine, vitamin B12 and omega-3 fatty acids. However, food-safety guidance must consider species-specific contaminants such as methylmercury. Appropriate species selection, portions and safety recommendations can help balance benefits and risks (Golden *et al.*, 2021; US FDA & EPA, 2024).

The health contribution also depends on preparation. Fresh, chilled or minimally processed fish differs nutritionally from heavily salted, smoked, battered or deep-fried products. Salt-preserved foods can increase sodium intake, while deep-frying increases energy density. Thus, recommendations should consider the organism, processing method, preparation and the overall dietary pattern.

The nutrition–environment nexus is also important. Some aquatic foods can provide substantial nutrients with comparatively low environmental pressures. Farmed bivalves and seaweeds generally have low feed and agricultural-land requirements, while some capture fisheries and efficient aquaculture systems can deliver nutrient-dense foods with relatively low greenhouse-

gas emissions (Gephart *et al.*, 2021; Koehn *et al.*, 2023). Environmental performance, however, varies among systems.

Food safety and post-harvest management are essential. Aquatic foods are highly perishable, and poor handling, temperature abuse and inadequate sanitation can cause microbial deterioration and foodborne illness. Aquatic environments can also contain pathogens, biotoxins, heavy metals and persistent contaminants. Cold-chain maintenance, hygienic handling, appropriate cooking and regulatory oversight help protect nutritional benefits (FAO & WHO, 2022).

Losses can occur during harvesting, transport, storage and processing through physical damage, microbial deterioration, oxidation and nutrient loss. Ice production, refrigeration, hygienic markets, improved processing and packaging can reduce losses, raise producer incomes and improve consumer availability (FAO, 2024). For small-scale fishing and farming households, aquatic foods can simultaneously provide food and income, although commercialisation may sometimes encourage sale rather than household consumption.

The literature therefore frames aquatic foods as part of an integrated nutrition–health–environment system. Their contribution depends on species, production, processing, frequency of consumption, affordability, access and the foods they replace. They offer strong potential for healthier and more sustainable diets when these factors are considered together (Golden *et al.*, 2021; Gephart *et al.*, 2021; Koehn *et al.*, 2023).

3. Livelihoods, Social Sustainability and the Role of Women

A sustainable aquatic-food system must be economically viable, socially inclusive, nutritionally beneficial and equitable. Fisheries and aquaculture support food, employment, income, cultural identity and social security across extensive value chains. These include hatchery workers, feed suppliers, equipment manufacturers, processors, transporters, wholesalers, retailers and informal workers. FAO’s Blue Transformation framework places livelihoods, nutrition, poverty reduction and equitable development alongside environmental sustainability (FAO, 2024).

Small-scale fisheries and aquaculture are especially important for household food security and local economies. FAO (2024) estimates that about 61.8 million people were engaged in primary fisheries and aquaculture production, with women representing about 24% of the primary-production workforce where sex-disaggregated data were available. Women constitute a much larger share of post-harvest employment, showing that production-focused statistics can underestimate their contribution.

Social sustainability also concerns who receives value from aquatic-food chains. Small producers may receive low prices while downstream actors capture more final value. Women and informal workers can face additional disadvantages because their activities may be poorly documented, weakly regulated or excluded from formal finance and institutions. Adam *et al.* (2024),

reviewing 202 studies, found that women participate throughout aquatic-food value chains but often remain less visible and less supported.

Women are particularly important in processing, drying, smoking, preservation, trading, retailing, marketing, aquaculture-related work, household food preparation and care. FAO (2024) reports women account for approximately 62% of workers in the post-harvest sector where sex-disaggregated data are available, compared with approximately 24% in primary fisheries and aquaculture. Post-harvest work links production to safe food, market availability and household nutrition.

Despite this contribution, women may have limited agency, unequal access to productive resources, limited control over income, restricted decision-making power and inadequate policy support (Adam *et al.*, 2024). Participation alone does not necessarily equal empowerment. Meaningful empowerment involves ownership or control of assets, access to finance and information, bargaining power, leadership and influence over decisions.

Gender equality should therefore be incorporated into the design, implementation and evaluation of aquatic-food policies rather than treated as a separate social objective. Women's self-help groups, producer cooperatives, community organisations and savings groups can strengthen access to finance, knowledge, technologies and collective bargaining. Their effectiveness depends on genuinely inclusive leadership and decision-making.

The distribution of benefits also matters for household nutrition. Women often influence food acquisition, preparation and allocation. Greater control over income and productive resources may increase capacity to allocate resources toward nutritious food, health and children's needs, although nutrition outcomes remain dependent on prices, preferences, knowledge, markets and household decision-making (Adam *et al.*, 2024).

Climate change adds another dimension. Changes in temperature, rainfall, water availability, storms, floods, droughts and ecosystem productivity affect aquatic livelihoods, but impacts are not gender neutral. Women in informal post-harvest activities may be particularly exposed to seasonal supply and market disruptions. Access to alternative livelihoods, finance, climate information, skills and social protection can strengthen resilience. Diversification into processing, cold-chain services, fish products, aquaculture inputs and digital marketing may create additional opportunities.

4. Community Aquaculture, Inclusive Value Chains and Sustainable Transformation

Evidence from India illustrates how aquatic-food production can link livelihoods, nutrition and women's empowerment. Dubey *et al.* (2024) examined a government-supported community-based aquaculture initiative in Odisha in which Women's Self-Help Groups participated in nutrition-sensitive carp–mola polyculture in community ponds. The approach integrates

commercially valuable carp with mola carplet (*Amblypharyngodon mola*), a small indigenous fish with nutritional importance.

Inclusive aquatic-food value chains should enable small-scale producers, women, youth and marginalised groups to benefit from economic growth. Key elements include fair market access, transparent pricing, finance, suitable technologies, safe working conditions and opportunities for value addition. Digital tools such as mobile payments, online marketing, digital advisory services, traceability and producer-to-consumer platforms may expand opportunities, but digitalisation can also reproduce inequality where women lack smartphones, connectivity, digital literacy or financial services.

Physical infrastructure is equally important. Cold storage, hygienic markets, processing facilities, transportation, improved drying technologies and packaging can reduce post-harvest losses and create value-added opportunities. Infrastructure should reflect women's needs because of their strong presence in post-harvest work. Safe workplaces, sanitation, suitable equipment and technical training can improve both working conditions and productivity (FAO, 2024).

Monitoring should move beyond counting female participation. Meaningful indicators include ownership of assets, control over income, access to finance, decision-making authority, leadership, bargaining power, information access, workload, food security, nutrition and resilience. Gender-transformative approaches need to address unequal power structures and social norms rather than merely adding women to existing programmes (Adam *et al.*, 2024).

Research Gaps

Although research on aquatic foods, blue-food systems, fisheries, aquaculture and sustainable diets has expanded substantially over the past decade, important conceptual, methodological and geographical gaps remain. The literature has increasingly established that aquatic foods can contribute simultaneously to nutrition, food security, livelihoods and environmental sustainability (Golden *et al.*, 2021; Gephart *et al.*, 2021; Crona *et al.*, 2023; Koehn *et al.*, 2023). However, the evidence base remains uneven, with considerable differences in the availability of species-specific nutritional information, environmental data, socioeconomic assessments and gender-disaggregated indicators. Much of the existing research also continues to evaluate fisheries, aquaculture, nutrition and sustainability as relatively separate domains. Future research therefore needs to move towards integrated, context-specific and interdisciplinary approaches capable of examining how aquatic foods influence human health, ecological integrity and livelihood resilience simultaneously.

Nutritional Characterisation of Locally Available and Underutilised Aquatic Species

One of the most important research gaps concerns the nutritional characterisation and promotion of locally available, small indigenous and underutilised aquatic species. Existing nutrition databases and food-composition studies frequently focus on commercially important species,

while relatively limited information is available for many small freshwater fish, indigenous species, molluscs, aquatic plants and seaweeds consumed at household or community levels. This represents a significant limitation because aquatic-food biodiversity is considerably greater than is reflected in conventional fisheries statistics and food-composition databases. Golden *et al.* (2021) demonstrated that substantial differences exist among aquatic species in their concentrations of calcium, iron, zinc, vitamin B12, omega-3 fatty acids and other essential nutrients. Consequently, treating aquatic foods as a single homogeneous category can underestimate their potential contribution to addressing specific nutritional deficiencies.

Small indigenous fish deserve particular attention because many species can be consumed whole, including bones and viscera, thereby providing minerals and micronutrients that may be present in lower concentrations in fillets of larger commercial fish (Bogard *et al.*, 2015; Golden *et al.*, 2021). Future research should therefore combine food-composition analysis, dietary surveys, nutrient-bioavailability studies and species-level consumption data to establish the true nutritional contribution of these resources. Greater attention is therefore needed to determine which locally available aquatic species that provide the greatest nutritional benefits and how they can be safely and affordably incorporated into traditional diets (Gephart *et al.*, 2021; Koehn *et al.*, 2023).

Integrating Nutrition and Environmental Sustainability

A second major research gap concerns the need for integrated nutrition–environment assessments. Much of the environmental literature evaluates aquatic foods using indicators such as greenhouse-gas emissions, land use, freshwater use, eutrophication and energy consumption, whereas nutrition research generally focuses on nutrient density and health outcomes. Although these two bodies of research are increasingly converging, they are still insufficiently integrated (Gephart *et al.*, 2021; Koehn *et al.*, 2023).

Gephart *et al.* (2021) demonstrated substantial variation in the environmental performance of different blue-food production systems. Farmed bivalves and seaweeds generally have comparatively low environmental pressures, while the environmental performance of capture fisheries and fed aquaculture varies according to species, production technology, feed, energy use and management practices. These findings suggest that future research should not simply ask whether aquatic foods are “sustainable,” but rather which aquatic foods, produced where, by which methods, for which consumers and with what nutritional benefits provide the most favourable overall outcomes. Life-cycle assessment could be combined with nutrient profiling, dietary modelling and socioeconomic analysis to identify aquatic-food pathways that maximise nutritional benefits while minimising environmental pressures. Such interdisciplinary approaches would strengthen the scientific basis for sustainable-diet recommendations (Gephart *et al.*, 2021; Crona *et al.*, 2023; Koehn *et al.*, 2023).

Gender As a Core Component of Aquatic-Food Sustainability Research

Adam *et al.* (2024) reviewed more than 200 studies and demonstrated that gender inequality in aquatic-food systems is associated with unequal agency, access to and control over resources, gendered norms, and limited participation in governance and decision-making. Their findings demonstrate that gender should not be treated as a supplementary social variable but as a structural component of aquatic-food-system transformation.

Future research should therefore examine who owns productive assets, who controls income, who makes production decisions, who has access to credit and technology, and who participates in governance. Merely recording the number of women involved in fisheries or aquaculture is insufficient because participation does not necessarily imply empowerment. Gender-responsive research should incorporate indicators of agency, decision-making, asset ownership, workload, financial control, leadership and access to markets (Adam *et al.*, 2024).

Post-Harvest Losses and Value Addition

Future studies should examine low-cost cold-chain technologies, solar drying, improved smoking systems, hygienic fermentation, packaging innovations and nutrient-preserving processing methods. Research should also investigate opportunities for converting processing by-products into food, feed, fertiliser, nutraceuticals and other value-added products, thereby connecting aquatic foods with circular-economy approaches (FAO, 2024).

Data, Methodological and Longitudinal Gaps

Digital technologies may provide new opportunities for improving data collection. Mobile surveys, remote sensing, electronic catch documentation, digital marketplaces and traceability systems could generate more timely information on aquatic-food production and value chains. Nevertheless, researchers should also investigate the digital divide, particularly among women, small-scale producers and remote communities, because digitalisation may reproduce existing inequalities if access to technology and digital literacy are uneven.

Conclusion

The future of aquatic foods lies in producing better, nourishing better and distributing benefits more fairly, rather than simply producing more. Integrating aquatic biodiversity, sustainable production, healthy diets, climate resilience, gender equality and circular value chains can transform blue foods into a powerful pathway towards inclusive and sustainable living.

References

1. Adam, R., Lam, R. D., Lozano Lazo, D. P., McDougall, C., Rajaratnam, S., Ouko, K. O., Pasani, C., Forsythe, L., & Rossignoli, C. M. (2024). Using a sustainable food systems framework to examine gender equality and women's empowerment in aquatic food systems. *Frontiers in Sustainable Food Systems*, 8, 1327798. <https://doi.org/10.3389/fsufs.2024.1327798>

2. Additional recent literature relevant to the review includes work on innovative aquatic protein sources, aquatic alternative proteins, climate vulnerability of blue foods, environmental performance, food environments and sustainable aquaculture. (n.d.). ScienceDirect. <https://www.sciencedirect.com/science/article/abs/pii/S0924224424001158>
3. Behsnilian, D., *et al.* (2022). Nutritional value and health benefits of fish and seafood: A review. *Foods*.
4. Bennett, A., & Belant, J. L. (2024). The global nutritional value of recreational inland fisheries. *Nature Food*, 5, 353–354. <https://doi.org/10.1038/s43016-024-00965-4>
5. Calder, P. C. (2017). Omega-3 fatty acids and inflammatory processes: From molecules to man. *Biochemical Society Transactions*, 45(5), 1105–1115.
6. Cao, L., Halpern, B. S., Troell, M., *et al.* (2023). Vulnerability of blue foods to human-induced environmental change. *Nature Sustainability*, 6, 1186–1198. <https://doi.org/10.1038/s41893-023-01156-y>
7. Crona, B. I., Wassénus, E., Jonell, M., Short, R., & Daw, T. M. (2023). Four ways blue foods can help achieve food system ambitions across nations. *Nature*, 616, 104–112. <https://doi.org/10.1038/s41586-023-05737-x>
8. Dubey, S. K., Padiyar, A. P., Chadag, V. M., Shenoy, N., Gaikwad, A. B., Ratha, B. C., & Belton, B. (2024). Scaling community-based aquaculture for enhanced nutrition and women's empowerment: Lessons from Odisha, India. *Frontiers in Sustainable Food Systems*, 8, 1412686. <https://doi.org/10.3389/fsufs.2024.1412686>
9. Food and Agriculture Organization of the United Nations, & World Health Organization. (2019). *Sustainable healthy diets: Guiding principles*. <https://www.fao.org/family-farming/detail/en/c/1261271/>
10. Food and Agriculture Organization of the United Nations, & World Health Organization. (2022). *Food safety aspects of fish and seafood*.
11. Food and Agriculture Organization of the United Nations, & World Health Organization. (2024). *Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption*. <https://www.who.int/publications/m/item/ad-hoc-joint-fao-who-expert-consultation-on-risks-and-benefits-of-fish-consumption>
12. Food and Agriculture Organization of the United Nations. (2012). *Sustainable diets and biodiversity: Directions and solutions for policy, research and action*. <https://www.fao.org/4/i3004e/i3004e00.htm>
13. Food and Agriculture Organization of the United Nations. (2021). *The role of aquatic loss and waste in sustainable healthy diets*. <https://www.fao.org/flw-in-fish-value-chains/resources/articles/the-role-of-aquatic-loss-and-waste-in-sustainable-healthy-diets/en/>

14. Food and Agriculture Organization of the United Nations. (2022). *The state of world fisheries and aquaculture 2022: Towards blue transformation*. <https://www.fao.org/4/cc0461en/online/sofia/2022/consumption-of-aquatic-foods.html>
15. Food and Agriculture Organization of the United Nations. (2023). *Pacific food systems: Recommendations for realizing the nutritional and health benefits of fish and other aquatic foods*. <https://www.fao.org/family-farming/detail/en/c/1644093/>
16. Food and Agriculture Organization of the United Nations. (2024a). *Gender in fisheries and aquaculture*. <https://www.fao.org/gender/learning-center/thematic-areas/gender-in-fisheries-and-aquaculture/2/en>
17. Food and Agriculture Organization of the United Nations. (2024b). *Guidelines for sustainable aquaculture*. <https://www.fao.org/guidelines-sustainable-aquaculture/about/en>
18. Food and Agriculture Organization of the United Nations. (2024c). *The state of world fisheries and aquaculture 2024: Blue transformation in action*.
19. Food and Agriculture Organization of the United Nations. (2025). *Guidelines for sustainable aquaculture*. <https://www.fao.org/guidelines-sustainable-aquaculture/en>
20. Farmery, A. K., O'Kane, G., McManus, A., & Green, B. S. (2021). Public health messages about fish consumption: A systematic review. *Public Health Nutrition*.
21. Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature*, 597, 360–365. <https://doi.org/10.1038/s41586-021-03889-2>
22. Golden, C. D., Koehn, J. Z., Shepon, A., *et al.* (2021). Aquatic foods to nourish nations. *Nature*, 598, 315–320. <https://doi.org/10.1038/s41586-021-03917-1>
23. Hasselberg, A. E., Frøyland, L., Kögel, T., Wik Markhus, M., Plata, J., van der Meeren, T., Sørhus, E., Sanden, M., Lunestad, B. T., Hannisdal, R. (2024). Maximizing the potential of sustainable aquatic food systems for global food security: Key opportunities and challenges. *Frontiers in Ocean Sustainability*, 2. <https://doi.org/10.3389/focsu.2024.1504689>
24. Hicks, C. C., Cohen, P. J., Graham, N. A. J. (2019). Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, 574, 95–98. <https://doi.org/10.1038/s41586-019-1592-6>
25. Kennedy, G., Ahern, M. B., Iannotti, L. L., Vie, S., Sherburne, L., & Thilsted, S. H. (2023). Considering the food environment can help to promote the consumption of aquatic foods for healthy diets. *Frontiers in Sustainable Food Systems*, 7, 1241548.
26. Kennedy, G., *et al.* (2023). Food environments and healthy diets: The role of availability, affordability and accessibility. *Global Food Security*.

27. Koehn, J. Z., Leape, J. P., & Allison, E. H. (2023). Aquatic foods at the nutrition–environment nexus. *Nature Sustainability*, 6, 1497–1498. <https://doi.org/10.1038/s41893-023-01229-y>
28. Mozaffarian, D., & Wu, J. H. Y. (2011). Omega-3 fatty acids and cardiovascular disease: Effects on risk factors, molecular pathways, and clinical events. *Journal of the American College of Cardiology*, 58(20), 2047–2067.
29. Njuki, J., Eissler, S., Malapit, H., Meinzen-Dick, R., Bryan, E., & Quisumbing, A. (2023). A review of evidence on gender equality, women's empowerment, and food systems. In *Gender equality and food systems*. Springer.
30. Pandey, V. K. (2025). Exploring the significance of emerging blue food processing technologies for sustainable development. *Food Research International*, 200, 115429. <https://www.sciencedirect.com/science/article/abs/pii/S0963996924014996>
31. U.S. Food and Drug Administration, & U.S. Environmental Protection Agency. (2024). *Advice about eating fish: For those who are pregnant or breastfeeding, and children*.
32. Vogliano, C., Kennedy, G., Thilsted, S., *et al.* (2024). Regenerative aquatic foods can be a win–win for human and planetary health. *Nature Food*, 5, 718–719. <https://doi.org/10.1038/s43016-024-01043-5>
33. Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawann, C., Kaushik, S., Mungkung, R., Naylor, R., Phillips, M., & Thilsted, S. H. (2014). *Improving productivity and environmental performance of aquaculture*. World Resources Institute.
34. World Economic Forum. (2024). *Investigating global aquatic food loss and waste*. <https://www.weforum.org/publications/investigating-global-aquatic-food-loss-and-waste/>

ECO-ANXIETY AND ADAPTATION: PSYCHOLOGICAL RESPONSES TO CLIMATE CHANGE

Kodukula Venkata Lakshmi Prudhvila

Department of Psychology

St. Joseph's College for Women (A), Visakhapatnam

Abstract

Climate change is increasingly recognized as a psychological stressor as much as an ecological one, giving rise to what is now termed 'eco-anxiety' - chronic worry, grief, and distress linked to environmental degradation and an uncertain ecological future. This paper examines the psychological underpinnings of climate-related distress through the lens of health and environmental psychology, focusing on how repeated exposure to climate threats shapes cognitive, emotional, and behavioral responses. Particular attention is given to vulnerable populations, especially adolescents and young adults, who report disproportionately high levels of climate-related anxiety and hopelessness. The paper explores the spectrum of coping responses to eco-anxiety, distinguishing adaptive strategies such as problem-focused engagement, collective action, and meaning-making from maladaptive responses including avoidance, denial, and emotional numbing, which may worsen psychological outcomes over time. It further situates eco-anxiety within a broader public health framework, arguing that unaddressed climate distress contributes to rising rates of anxiety, depression, and diminished community well-being. Protective factors including social support, environmental self-efficacy, and community resilience are discussed as key buffers against psychological harm. By integrating psychological theory with public health perspectives, this paper advocates for embedding mental health support within climate adaptation and policy frameworks, and highlights the need for empirically validated interventions that build psychological resilience in the face of ecological uncertainty. Ultimately, the paper positions psychological well-being as a core component of sustainable, human-centered climate response.

Keywords: Eco-Anxiety, Climate Change, Mental Health, Coping, Resilience, Climate Adaptation, Environmental Psychology.

Introduction

Climate change is not only a physical and ecological crisis; it is also a sustained psychological stressor. Rising temperatures, extreme weather, ecosystem degradation, displacement, and threats to livelihoods can produce fear, grief, anger, helplessness, and uncertainty. These experiences may occur after direct exposure to a climate-related event, through concern about anticipated harms, or through awareness of losses affecting other people and species (Doherty & Clayton,

2011; Hayes *et al.*, 2018). The Intergovernmental Panel on Climate Change (IPCC, 2022) emphasizes that climate impacts are distributed unevenly, meaning that psychological consequences are shaped by social position, access to resources, prior adversity, and the capacity of communities to adapt.

The term eco-anxiety has entered psychological and public-health discussion to describe distress associated with environmental change. It is used broadly and does not, by itself, signify a psychiatric diagnosis. Concern may be proportionate to objectively serious threats and may motivate protective action rather than indicate dysfunction (Clayton, 2020; Pihkala, 2020). The clinically important question is therefore not whether a person is worried about climate change, but whether distress becomes persistent, overwhelming, and impairing, or interacts with other vulnerabilities to compromise functioning and well-being.

This paper presents an integrative narrative review of psychological responses to climate change. It synthesizes health psychology, environmental psychology, stress and appraisal theory, conservation of resources theory, developmental psychology, trauma and grief perspectives, collective efficacy, and resilience theory. The central thesis is that climate-related distress should be understood as a heterogeneous response to real and unequal threats: it can impair health when people experience uncontrollable loss and depleted resources, but it can also support adaptation when psychological support, social connection, agency, and meaningful collective action are available.

The review does not report original participants, instruments, statistical analyses, or fieldwork. Instead, it draws together peer-reviewed scholarship and authoritative guidance to clarify pathways from climate change to psychological distress and to identify psychologically informed responses. This approach is appropriate for a rapidly developing topic, although the limitations of narrative synthesis and uneven evidence are considered later (Charlson *et al.*, 2021; World Health Organization [WHO], 2022).

Conceptualising Eco-Anxiety

Eco-anxiety is best conceptualized as a spectrum rather than a single symptom or disorder. At one end is realistic concern, which may sharpen attention, encourage information seeking, and support preparation. At the other end are anxiety, despair, intrusive worry, sleep disruption, avoidance, or functional impairment. Between these poles are forms of ecological grief, moral distress, anticipatory loss, and frustration with institutional inaction (Clayton, 2020; Pihkala, 2020). A spectrum model avoids both pathologizing reasonable concern and minimizing distress that requires clinical attention.

Environmental psychology helps explain why climate change can affect identity, place attachment, and perceived safety. Places are not merely physical settings; they support memory, belonging, continuity, and daily routines. When landscapes change or become unsafe, people

may experience a threat to personal and collective identity. Ecological grief describes sorrow connected with actual or anticipated losses in ecosystems, species, cultural practices, and ways of life (Cunsolo & Ellis, 2018). Cunsolo Willox *et al.* (2020) argue that grief and anxiety can be healthy responses when they remain connected to relationships, recognition of loss, and possibilities for action.

The concept also requires attention to context. A person displaced by flooding, a farmer facing livelihood uncertainty, an adolescent concerned about an unstable future, and a professional repeatedly exposed to climate-related information may all experience climate distress, but their appraisals and resources differ. Eco-anxiety therefore cannot be interpreted independently of social inequality, exposure, historical injustice, and access to support (Berry *et al.*, 2018; IPCC, 2022).

Psychological Mechanisms Linking Climate Change and Distress

Stress and appraisal theory provides a useful account of how climate threats become psychologically significant. Lazarus and Folkman (1984) distinguish primary appraisal, or the evaluation of threat, from secondary appraisal, or the evaluation of available coping resources. Climate change can be appraised as severe, pervasive, uncertain, and difficult for any individual to control. When perceived demands exceed perceived resources, distress is likely to intensify. Appraisals are not simply cognitive errors: they are shaped by credible scientific information, lived experience, social narratives, and institutional responses.

Conservation of resources theory adds that stress emerges when valued resources are threatened, lost, or insufficiently replenished (Hobfoll, 1989). Climate-related hazards may threaten housing, income, health, social networks, cultural continuity, and a sense of future security at the same time. Resource loss can produce “loss spirals” in which one disruption reduces the ability to prepare for the next. Conversely, social support, stable services, financial security, and opportunities for participation can create resource caravans that help people recover and adapt (Berry *et al.*, 2018; Hayes *et al.*, 2018).

Climate distress also travels through direct, indirect, and psychosocial pathways. Direct pathways include injury, heat exposure, disaster trauma, displacement, and bereavement. Indirect pathways include food and water insecurity, livelihood disruption, economic strain, conflict, and interrupted education. Psychosocial pathways include repeated media exposure, uncertainty, moral distress, ecological grief, perceived betrayal by institutions, and the loss of future agency (Doherty & Clayton, 2011; Charlson *et al.*, 2021). These pathways may accumulate over time rather than appear as a single event.

The table 1 illustrates why no single intervention can address all climate-related distress. Trauma-informed support may be necessary after a disaster, while community organizing or policy advocacy may be more appropriate for moral distress and perceived institutional failure. A

health-psychology perspective therefore links emotional well-being with prevention, risk communication, behavior change, and the social determinants of health (WHO, 2022).

Table 1: Psychological impact across direct, indirect, and psychosocial exposure pathways

Pathway	Psychological Process	Possible Response
Direct exposure	Threat appraisal, trauma, resource loss	Acute stress, grief, hypervigilance, recovery efforts
Indirect disruption	Uncertainty, role strain, loss of control	Anxiety, depression, withdrawal, problem solving
Psychosocial exposure	Moral distress, ecological grief, future uncertainty	Anger, hopelessness, meaning-making, collective action

Cognitive, Emotional, and Behavioural Responses

Climate-related cognition often involves threat monitoring, rumination, catastrophic imagery, uncertainty intolerance, and repeated attempts to forecast an unpredictable future. These processes may help people identify risks, but they can become exhausting when information is continuous and action appears ineffective. Climate anxiety may also involve self-questioning about consumption, responsibility, and complicity, producing moral distress or guilt (Clayton, 2020; Pihkala, 2020).

Emotional responses include fear, sadness, anger, shame, grief, frustration, and numbness. Ecological grief differs from grief after one discrete death because losses may be gradual, ambiguous, collective, and ongoing. People may mourn species, landscapes, cultural practices, or anticipated life possibilities without receiving social recognition for that grief (Cunsolo & Ellis, 2018). Emotional responses can coexist: anger may energize advocacy, while grief may signal attachment and motivate care.

Behavioral responses range from preparation and conservation to avoidance, denial, disengagement, and compulsive information seeking. Ojala's (2012) work on young people shows that constructive hope can support engagement when it is grounded in reflection and collective possibility, whereas false reassurance may suppress meaningful action. Behavioral consequences are therefore shaped by perceived efficacy: people are more likely to act when they believe their actions matter and are supported by others.

Climate distress can become clinically significant when symptoms are severe, persistent, and functionally impairing, especially when combined with prior anxiety, depression, trauma, or material insecurity. However, distress should not be treated as evidence that climate concern is irrational. The clinical task is to validate the reality of the threat, assess impairment and safety, and support flexible coping rather than simply reduce concern (Clayton, 2020; WHO, 2022).

Developmental and Social Vulnerability: Adolescents and Young Adults

Adolescents and young adults occupy a distinctive developmental position. Developmental psychology emphasizes that this period involves identity formation, expanding moral concern, educational and occupational transition, and the construction of an imagined future. Climate change enters these developmental tasks by making adulthood, family formation, employment, and place attachment feel uncertain. The ecological systems perspective further shows that development is shaped by interacting family, school, community, institutional, and cultural environments (Bronfenbrenner, 1979).

The global survey by Hickman *et al.* (2021) documented substantial climate-related worry among children and young people and linked distress with perceptions that governments were failing to respond adequately. Such findings should not be interpreted as evidence that young people are inherently fragile. Rather, young people may be responding coherently to a contradiction between scientific warnings, visible climate impacts, and limited adult or institutional action. Ojala (2012) shows that constructive coping depends partly on whether young people can combine realistic concern with hope, agency, and opportunities for participation. Social vulnerability modifies both exposure and recovery. Low-income households, displaced people, Indigenous communities, climate-dependent workers, people with disabilities, and those living with discrimination may face greater risks and fewer recovery resources (IPCC, 2022; Charlson *et al.*, 2021). In India, climate-related heat, flooding, water stress, agricultural disruption, and displacement may intersect with existing inequalities and livelihood dependence; the psychological implications must therefore be considered alongside social and environmental conditions rather than reduced to individual resilience (IPCC, 2022).

Schools, universities, families, and youth organizations can serve as developmental settings for psychological protection. They can provide accurate information, emotional acknowledgment, practical preparedness, and opportunities for collective action. At the same time, educational institutions should avoid placing the burden of climate adaptation on young people without addressing structural causes and institutional responsibility (Hickman *et al.*, 2021; WHO, 2022).

Adaptive and Maladaptive Coping

Stress and appraisal theory distinguishes problem-focused coping, emotion-focused coping, and meaning-focused processes, while recognizing that their usefulness depends on context (Lazarus & Folkman, 1984). Problem-focused coping may include preparedness, conservation, political participation, and seeking reliable information. Emotion-focused coping may include emotional expression, rest, therapeutic support, and practices that regulate arousal. Meaning-focused coping helps people preserve purpose when outcomes cannot be controlled immediately.

Adaptive coping is flexible, socially connected, and proportionate to available resources. It allows a person to acknowledge danger without becoming consumed by it, to act without

assuming individual responsibility for solving a collective crisis, and to rest without interpreting rest as indifference. Collective action is especially important because it converts private worry into shared efficacy and can challenge the isolation that accompanies eco-anxiety (Bandura, 2000; Ojala, 2012).

Maladaptive coping includes persistent avoidance, denial, emotional numbing, compulsive checking, self-blame, and disengagement from relationships or daily responsibilities. These responses may provide short-term relief but can maintain anxiety by preventing emotional processing or practical action. Conservation of resources theory suggests that avoidance may become more likely when people are already depleted and perceive no realistic route to recovery (Hobfoll, 1989). A nonjudgmental approach is essential: clinicians and educators should understand what a coping response protects before attempting to change it.

Coping should also be evaluated ethically. Encouraging individual lifestyle changes without addressing policy, infrastructure, and corporate responsibility can intensify guilt and obscure structural determinants. Conversely, political engagement without boundaries can produce burnout. A psychologically informed approach supports both individual self-care and collective, institutional, and policy-level action (Clayton *et al.*, 2017; Hayes *et al.*, 2018).

Protective Factors: Support, Efficacy, Meaning, and Resilience

Social support is a central protective factor because it provides emotional validation, practical assistance, information, and a sense of belonging. Supportive relationships can normalize climate emotions without trivializing them and can help people appraise risks more accurately. In disaster and climate contexts, social networks also provide access to material resources and recovery pathways, making social connection both a psychological and structural resource (Berry *et al.*, 2018; Hayes *et al.*, 2018).

Environmental self-efficacy refers to the belief that one can participate meaningfully in environmental action. Self-efficacy does not require believing that an individual can control the climate system; it involves confidence in contributing to achievable personal, community, or political goals. Collective efficacy extends this principle by emphasizing shared beliefs that a group can organize and produce change (Bandura, 2000). These beliefs can reduce helplessness and support sustained engagement when paired with realistic goals.

Meaning-making helps people integrate climate disruption into a coherent moral and personal framework. It may involve cultural traditions, spirituality, professional purpose, care for future generations, or a commitment to justice. Meaning-making should not be used to impose optimism or imply that suffering is beneficial. Its value lies in helping people identify what remains important and how values can guide action under uncertainty (Pihkala, 2020; Cunsolo Willox *et al.*, 2020).

Community resilience theory describes resilience as a set of capacities rather than a fixed trait. These capacities include social connectedness, communication, economic resources, trusted leadership, community competence, and the ability to learn after disruption (Norris *et al.*, 2008). Resilience theory similarly emphasizes ordinary protective systems—relationships, routines, self-regulation, and supportive institutions—rather than exceptional individual strength (Masten, 2014). A resilience approach must therefore ask whether systems are enabling recovery, not merely whether individuals are coping well.

Key Synthesis:

Psychological protection is strongest when people can name climate emotions, access trustworthy relationships and services, participate in meaningful collective action, and see institutions responding credibly. Resilience is not acceptance of preventable harm; it is the capacity to preserve well-being and agency while pursuing safer and more just conditions.

Public-Health and Clinical Implications

Climate change expands the remit of public mental health. Prevention requires attention to housing, livelihoods, health systems, education, social protection, disaster preparedness, and equitable access to adaptation resources. The WHO (2022) recommends integrating mental health into climate policy and adaptation planning rather than treating psychological support as an afterthought. This is consistent with systems approaches that recognize reciprocal relationships among ecological conditions, social institutions, and mental health (Berry *et al.*, 2018).

Clinical services should use a stepped and trauma-informed model. Universal measures may include psychoeducation, supportive communication, peer connection, and community preparedness. More intensive services are appropriate when people experience persistent impairment, severe anxiety or depression, trauma symptoms, substance misuse, or safety concerns. Clinicians should assess direct exposure, displacement, bereavement, financial strain, prior mental-health history, and cultural meanings of place and loss (Charlson *et al.*, 2021; Hayes *et al.*, 2018).

Climate-sensitive practice also requires professional preparation. Psychologists, counselors, social workers, teachers, and health professionals need language for ecological grief and moral distress, as well as skills for risk communication, group facilitation, and referral. Services should avoid dismissing climate concerns as irrational or responding with premature reassurance. Validation, collaborative formulation, practical problem solving, and restoration of agency are more appropriate responses (Clayton *et al.*, 2017; WHO, 2022).

Climate Adaptation and Psychologically Informed Interventions

Psychologically informed climate adaptation begins with participation. Communities should be involved in identifying risks, defining acceptable adaptation, and deciding how support is

delivered. Participation can strengthen collective efficacy and reduce the experience of being acted upon by distant institutions. It can also reveal culturally specific forms of loss, care, and recovery that standardized programs may overlook (Bandura, 2000; Norris *et al.*, 2008).

At the individual and group levels, interventions may combine evidence-based anxiety-management skills with climate-specific psychoeducation, values clarification, grief processing, and action planning. Group formats can be particularly useful because they reduce isolation and enable shared meaning-making. Interventions should distinguish controllable from uncontrollable problems, establish boundaries around media exposure, encourage restorative activities, and support constructive hope rather than denial (Ojala, 2012; Pihkala, 2020).

At the institutional level, schools and universities can develop climate-emotion curricula, peer-support structures, referral pathways, and opportunities for service learning or civic participation. Workplaces and health services can prepare for climate-related stress, protect staff from repeated exposure, and include psychosocial support in emergency plans. Public communication should be scientifically accurate, emotionally attuned, culturally responsive, and paired with visible pathways for action (Clayton *et al.*, 2017; WHO, 2022).

Adaptation planning should also recognize that psychological well-being depends on material conditions. Cooling centers, safe housing, livelihood protection, accessible transportation, reliable communication, and rapid social assistance may prevent distress from escalating. Psychological services cannot compensate for unsafe infrastructure or avoidable displacement. The IPCC (2022) therefore supports an approach that combines physical adaptation, social justice, and mental-health protection.

Conclusion

Eco-anxiety is a psychologically meaningful response to a real, unequal, and continuing crisis. It is not automatically a psychiatric disorder, and realistic concern should not be pathologized. At the same time, climate distress can become clinically impairing when threat exposure, resource loss, uncertainty, grief, and perceived powerlessness exceed a person's coping capacity. Stress and appraisal theory, conservation of resources theory, environmental psychology, trauma and grief perspectives, developmental psychology, collective efficacy, and resilience theory together show why responses vary across people and contexts.

The central argument is that psychological well-being must be treated as a core component of climate adaptation rather than as a secondary consequence. Effective responses validate emotion, protect material and social resources, strengthen individual and collective agency, support meaning-making, and provide accessible clinical care when impairment occurs. A sustainable, human-centered climate response therefore requires both ecological action and psychological infrastructure: institutions that communicate credibly, communities that organize support, and services that help people face uncertainty without surrendering hope or responsibility.

References

1. Bandura, A. (2000). Exercise of human agency through collective efficacy. *Current Directions in Psychological Science*, 9(3), 75–78. <https://doi.org/10.1111/1467-8721.00064>
2. Berry, H. L., Waite, T. D., Dear, K. B. G., Capon, A. G., & Murray, V. (2018). The case for systems thinking about climate change and mental health. *Nature Climate Change*, 8(4), 282–290. <https://doi.org/10.1038/s41558-018-0102-4>
3. Bronfenbrenner, U. (1979). *The ecology of human development: Experiments by nature and design*. Harvard University Press.
4. Charlson, F., Ali, S., Benmarhnia, T., Pearl, M., Massazza, A., Augustinavicius, J., & Scott, J. G. (2021). Climate change and mental health: A scoping review. *International Journal of Environmental Research and Public Health*, 18(9), 4486. <https://doi.org/10.3390/ijerph18094486>
5. Clayton, S. (2020). Climate anxiety: Psychological responses to climate change. *Journal of Anxiety Disorders*, 74, 102263. <https://doi.org/10.1016/j.janxdis.2020.102263>
6. Clayton, S., & Karazsia, B. T. (2020). Development and validation of a measure of climate change anxiety. *Journal of Environmental Psychology*, 69, 101434. <https://doi.org/10.1016/j.jenvp.2020.101434>
7. Clayton, S., Manning, C. M., Krygsmann, K., & Speiser, M. (2017). *Mental health and our changing climate: Impacts, implications, and guidance*. American Psychological Association and ecoAmerica.
8. Cunsolo, A., & Ellis, N. R. (2018). Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, 8(4), 275–281. <https://doi.org/10.1038/s41558-018-0092-2>
9. Cunsolo Willox, A., Ellis, N. R., Middleton, J., Davis, H. J., & Cunsolo, M. (2020). Ecological grief and anxiety: The start of a healthy response to climate change? *The Lancet Planetary Health*, 4(7), e261–e263. [https://doi.org/10.1016/S2542-5196\(20\)30144-3](https://doi.org/10.1016/S2542-5196(20)30144-3)
10. Doherty, T. J., & Clayton, S. (2011). The psychological impacts of global climate change. *American Psychologist*, 66(4), 265–276. <https://doi.org/10.1037/a0023141>
11. Fritze, J. G., Blashki, G., Burke, S., & Wiseman, J. (2008). Hope, despair and transformation: Climate change and the promotion of mental health and wellbeing. *International Journal of Mental Health Systems*, 2, Article 13. <https://doi.org/10.1186/1752-4458-2-13>
12. Hayes, K., Blashki, G., Wiseman, J., Burke, S., & Reifels, L. (2018). Climate change and mental health: Risks, impacts and priority actions. *International Journal of Mental Health Systems*, 12, Article 28. <https://doi.org/10.1186/s13033-018-0210-6>

13. Hickman, C., Marks, E., Pihkala, P., Clayton, S., Lewandowski, R. E., Mayall, E. E., Wray, B., Mellor, C., & van Susteren, L. (2021). Climate anxiety in children and young people and their beliefs about government responses to climate change: A global survey. *The Lancet Planetary Health*, 5(12), e863–e873. [https://doi.org/10.1016/S2542-5196\(21\)00278-3](https://doi.org/10.1016/S2542-5196(21)00278-3)
14. Hobfoll, S. E. (1989). Conservation of resources: A new attempt at conceptualizing stress. *American Psychologist*, 44(3), 513–524. <https://doi.org/10.1037/0003-066X.44.3.513>
15. Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://doi.org/10.1017/9781009325844>
16. Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal, and coping*. Springer.
17. Masten, A. S. (2014). *Ordinary magic: Resilience in development*. Guilford Press.
18. Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, 41(1–2), 127–150.

CONVERGENCE OF SUSTAINABLE FOOD PACKAGING AND INFLUENCE OF CONSUMER PERCEPTION ON HEALTH

Glory Joanna Manne and Karri Jagannadham

Department of Clinical Nutrition Dietetics and Food Science,

School of Allied Health care Sciences,

Malla Reddy University, Hyderabad, Telangana 500043, India

Abstract

Sustainable food packaging has emerged as a pivotal intersection between environmental sustainability, food safety, and public health in the contemporary era. With the escalating environmental concerns associated with conventional plastic packaging and growing awareness of its potential health hazards, consumers are increasingly shifting their attention towards eco-friendly and sustainable packaging alternatives. The present study explores the convergence of sustainable food packaging and its influence on consumer perception and health-related choices. The primary objective is to understand how consumers perceive sustainable packaging materials such as biodegradable, compostable, paper-based, and reusable packaging and how this perception shapes their health-conscious purchasing decisions. The study concludes that promoting sustainable food packaging requires collaborative efforts from policymakers, food industries, and health educators to enhance consumer education and accessibility. Strengthening the convergence between sustainability and health perception can foster sustainable living practices and contribute to both environmental protection and improved public health outcomes.

Keywords: Sustainable Food Packaging, Consumer Perception, Consumer Health, Environmental Sustainability, Sustainable Living.

1. Introduction to Sustainable Food Packaging

1.1. Need for Sustainable Packaging in Food Industry

Plastic packaging, which makes up around 40% of all plastic consumption, is crucial to the world's food sector. Food and FMCG packaging accounted for a significant portion of the 4.1 million tons of plastic trash generated in India in 2022–2023, according to the Central Pollution Control Board. Three factors are driving the demand for sustainable packaging: environmental contamination brought on by non-biodegradable plastics, health hazards from chemical leaching and microplastics, and shifting consumer preferences for environmentally and health-conscious goods. Conventional packing contributes to greenhouse gas emissions, marine pollution, and landfill accumulation. Sustainable packaging is now not only an option for the environment but also required by law thanks to the Ministry of Environment, Forests, and Climate Change's Plastic Waste Management Rules, which require the decrease of single-use plastics. [3,9,10].

1.2 Evolution from Conventional to Sustainable Packaging

Due to their affordability and practicality, petroleum-based plastics replaced glass and metal in conventional packaging during the 1960s. But by the 2000s, the effects on the ecosystem were clear. There were three stages in the transition to sustainable packaging: Phase 1: Paper and glass packaging that can be recycled; Phase 2: Biodegradable plastics like PLA; Phase 3: Advanced sustainable packaging that includes edible films, agricultural waste, and active-intelligent systems. In the current phase, agricultural leftovers such as orange-peel pectin, jackfruit seeds, rice straw, and soybeans are transformed into high-value packaging materials under the waste-to-wealth idea. By starting research on microplastic contamination and emphasizing the health aspect of the packaging changeover, the Food Safety and Standards Authority of India has accelerated this transformation. [11,12,8].

2. Types and Classification of Sustainable Food Packaging Materials

2.1 Biodegradable Packaging

Under composting conditions, microorganisms can break down biodegradable packaging into natural materials in 60–180 days. Usually, cellulose, pectin, and starch are used to make it. According to studies, orange peel pectin films plasticized with glycerol demonstrate good elasticity and complete biodegradation, which makes them appropriate for use in baked goods and fruits. The benefit is that there are no microplastic production and less environmental persistence [12].

2.3 Compostable Packaging

A subset of biodegradable packaging, compostable packaging decomposes into non-toxic compost in commercial composting facilities. The most popular bioplastics that can be composted are PLA and PHA, which are made from corn starch and microbial fermentation. They are utilized for cutlery, cups, and meal trays.

2.4 Edible Packaging

Polysaccharides, proteins, and lipids that can be eaten with food are used to make edible packaging. It is generally regarded as safe and has the ability to produce zero waste. Caseinate-carboxymethyl chitosan membranes combined with soybean oil for enhanced water resistance, appropriate for sachets and candy wrapping, are examples of recent inventions [12].

2.5 Recyclable and Reusable Packaging

Glass, paper, and bio-PET are examples of recyclable packaging materials that can be processed again. Reusable packaging reduces overall package demand by emphasizing numerous use cycles, which is consistent with the concepts of the circular economy.

2.6 Bioplastics - PLA, PHA, Starch-based films

Plastics made from renewable biomass are known as bioplastics. Improved tensile strength and barrier qualities have been demonstrated by PLA made from corn starch, PHA made from

bacterial fermentation, and starch-based films made from cassava and jackfruit seed waste supplemented with rice straw cellulose. These materials are being used more frequently for membrane-type food packaging since they have a low carbon impact [8].

3. Using Agricultural Waste to Make Sustainable Packaging

3.1 Waste from Fruit and Vegetable Peels

Every year, India produces more than 100 million tons of fruit and vegetable waste. Pectin, starch, and cellulose are abundant in orange peel, banana peel, and jackfruit seeds. Orange peel pectin is a great polymer for making films. Glycerol-plasticized pectin films are completely biodegradable and exhibit elongation of up to 25%. This valorization lowers the cost of raw materials and promotes waste-to-wealth.

3.2 Cereal Husk and Straw

35–45% cellulose is found in cereal straw and husk, such as rice straw, wheat straw, and rice husk. By acting as a natural reinforcement, cellulose derived from rice straw increases the mechanical strength of starch films by 40–60%. Additionally, this strategy avoids stubble burning, which is a significant environmental problem in North India.

3.3 Sources Based on Proteins and Polysaccharides

Functional qualities are improved by proteins like casein and soy protein as well as polysaccharides like chitosan and carboxymethyl cellulose. For instance, caseinate-carboxymethyl chitosan films containing soybean oil have enhanced antibacterial activity and water vapor barrier, prolonging the shelf life of perishable items. Such environmentally friendly materials are essential to cutting-edge packaging methods [12].

4. Four Useful Features of Eco-Friendly Packaging

4.1 Characteristics of Barriers

It is crucial to have barrier qualities against water vapor transmission rate (WVTR) and oxygen transmission rate (OTR). While bioplastics now achieve 40–80 cc/m²/day, conventional plastics have an OTR of less than 10 cc/m²/day; this needs to be improved by the use of nanocomposites and multilayer architectures.

4.2 Mechanical Characteristics

Tensile strength, elongation at break, and puncture resistance are examples of mechanical characteristics. The tensile strength of cellulose-reinforced starch-based films is 15–25 MPa, while that of LDPE is 20–30 MPa. Glycerol and other plasticizers increase flexibility but decrease strength, necessitating adjustment.

4.3 Antioxidant and Antimicrobial Characteristics

Antimicrobial and antioxidant qualities are added by the use of essential oils, natural extracts, and nanoparticles. By preventing microbial growth and delaying lipid degradation, this active packaging improves health safety and lessens the need for artificial preservatives.

4.4 Extension of Shelf Life

Improved barrier and active properties lead to a prolongation of shelf life. Studies show that employing edible antimicrobial coatings can extend the shelf life of baked goods by three to five days. However, Lin *et al.* pointed out that in order for bioplastics to compete with conventional plastics in commercial applications, functional enhancements are still needed [8].

5. Five Aspects of Food Packaging That Affect Health

5.1 Food Packaging and Migration Concerns

Chemicals migrate as a result of direct interactions between food and food packaging. Temperature, fat content, and acidic pH all enhance migration. Conventional plastics pose health hazards due to their significant monomer and additive migration into food.

5.2 Conventional Packaging's Microplastics and Nano plastics

During usage and disposal, conventional plastics break down into microplastics (less than 5 mm) and nano plastics (less than 1000 nm). These have been found in processed foods, bottled water, sea salt, and honey. Microplastics have the ability to pass through biological barriers, build up in tissues, and induce inflammation and oxidative stress. Recognizing microplastic contamination as a growing hazard to food safety, FSSAI initiated a nationwide effort in 2024 to measure it in Indian foods [11].

5.3 Chemical Leaching: Phthalates and BPA

Endocrine disruptors include phthalates from PVC and bisphenol A (BPA) from polycarbonate. BPA is associated with cancer, obesity, and reproductive issues since it resembles oestrogen. Hormonal processes are disrupted by phthalates. According to studies, heating causes BPA migration to increase 50 times.

5.4 Benefits of Sustainable Packaging for Health and Safety

Natural polymer-based sustainable packaging has little migration, is free of BPA and phthalates, and doesn't produce microplastics when it breaks down. It provides health and safety benefits and is widely acknowledged as safe.

6. Theoretical Framework for Consumer Perception

6.1 The Idea of Consumer Behaviour and Perception

The process through which people choose, arrange, and interpret inputs to create a meaningful image of a product is known as consumer perception. Subjective perception has a greater impact on purchasing decisions than objective reality. Acceptance of food packaging is influenced by perceptions of sustainability and health [1].

6.2 Visual, Cognitive, and Emotional Factors Affecting Perception

Material, colour, shape, and labelling are examples of visual factors. According to studies, people believe that natural materials like kraft paper and green are healthier and more sustainable than plastic. Environmental awareness and health consciousness are examples of cognitive

factors. Trust and guilt related to plastic use are examples of emotional factors. Berthold *et al.* showed that colour and substance had a big impact on willingness to buy [2].

6.3 Health Belief Model and Planned Behaviour Theories

According to the Theory of Planned Behaviour, intention is influenced by attitudes toward sustainable packaging, perceived behavioural control (price, availability), and subjective norms (peer pressure). According to the Health Belief Model, adoption is driven by perceived health hazards associated with traditional plastics and perceived advantages of sustainable packaging. According to Atta-Delgado *et al.*, customer perceptions of sustainable solutions are influenced by both environmental and health attitudes. [1,7].

7. How Consumers View Sustainable Food Packaging

7.1 Perceived Eco-Friendliness and Sustainability

While plastic is seen as unhealthy and harmful to the environment, consumers typically equate paper, glass, and bioplastics with being healthy and environmentally friendly. Brand loyalty and image are impacted by this perspective. [2,7].

7.2 Packaging Material, Colour, and Labelling Influence

Colour and material have a significant influence. Perceived sustainability is improved by earthy hues, a matte texture, and green labelling. Labels like organic, BPA-free, plastic-free, and compostable foster trust. According to Duarte *et al.*, one important factor influencing purchase intention is labelling trustworthiness [4].

7.3 Willingness to Invest in Eco-Friendly Packaging

Young, educated, and health-conscious consumers are more willing to spend more for sustainable packaging. There is willingness in India, but price sensitivity is still a barrier. If health benefits are made evident, consumers are willing to spend an additional 5–10%. [4,7].

7.4 Sustainable Packaging Claims' Perception-Reality Disparity

Terms like "biodegradable" and "compostable" are frequently misunderstood by consumers, which results in incorrect disposal and scepticism. Concerns about greenwashing surface when statements are unsupported. Horsthuis *et al.* emphasized the necessity of using open communication and education to bridge the perception-reality gap [6].

8. The Convergence of Packaging, Sustainability, and Health Perception

8.1 How Health Consciousness is Shaped by Sustainable Packaging

By serving as a cue for naturalness, little processing, and safety, sustainable packaging influences health consciousness. Customers' dietary decisions and health-related behaviours are influenced by their unconscious association of eco-friendly packaging with nutritious products.

8.2 Sustainable Packaging Consumer Association with Food Safety and Health

Sustainable packaging is linked by consumers to organic, chemical-free, and safe food. This "health halo effect" suggests that, while having the same nutritional value, food in biodegradable

packaging is seen as safer, healthier, and of higher quality. This correlation is more pronounced in sectors that prioritize health.

8.3 The Impact of Eco-labels and Green Marketing on Health Perception

The convergence of sustainability and health is reinforced by green marketing techniques that include phrases like natural, earth-friendly, BPA-free, and compostable. Eco-labels impact consumers' willingness to buy sustainable packaging products and increase their perceived health value. Purchase intention might rise by 25–30% when green marketing is done well. [1,8,4].

9. The Function of Policy Interventions and Government Regulations

9.1 India's Plastic Waste Management Regulations

The Plastic Waste Management Rules 2016 and their 2022 and 2024 modifications prohibit 19 single-use plastics, impose Extended Producer Responsibility, and encourage the use of packaging made from agricultural waste and compostable plastics [9].

9.2 FSSAI Guidelines Regarding Microplastic Contamination and Food Packaging

FSSAI regulations forbid using recycled plastics for food contact and require the use of acceptable food-grade packaging materials. The FSSAI initiated a study in 2024 to evaluate microplastic contamination in Indian food, signifying a change in packaging restrictions to ones that are more focused on health [11].

9.3 International Initiatives: FDA and EU Views

The EU Circular Economy Action Plan, which promotes bio-based packaging, the US FDA's limits on food contact substances, and the EU Single-Use Plastics Directive 2019, which prohibits single-use plastics, are examples of global initiatives. Data on plastic trash production and compliance status in India may be found in the Central Pollution Control Board Annual Report 2022–2023. [3,9,10].

10. Obstacles and Prospects for the Future

10.1 Technical Difficulties with Biodegradable Packaging

Poor moisture barrier, low heat sealability, high production costs (20–30% higher than conventional), restricted scalability, and short film shelf life are examples of technical difficulties.

10.2 Barriers to Consumer Awareness and Acceptance

The distinction between biodegradable and compostable materials, appropriate disposal techniques, and real health benefits are still not well understood by consumers. Higher costs and scepticism brought on by greenwashing are obstacles to acceptance. In their systematic review, Du Rietz and Kremel came to the conclusion that consumer behaviour presents both opportunities and challenges for circular packaging [5].

10.3 Upcoming Trends: Intelligent, Active, and Smart Sustainable Packaging

Future trends include nanotechnology-enhanced bioplastics, smart packaging with freshness indicators, active packaging with antimicrobial agents, and intelligent packaging with QR codes that provide nutritional information and traceability. Next-generation packaging that is economically feasible, health-safe, and really sustainable will be driven by the integration of biotechnology, nanotechnology, and agricultural waste [12].

11 Summary and Research Gap

11.1 Summary of Literature

Extensive research on the creation of sustainable packaging materials from agricultural waste and consumer attitudes about sustainability separately may be found in the literature. Conventional plastics' functional characteristics, health dangers, and factors influencing customer perception have all been researched. In order to promote sustainable alternatives, regulatory frameworks are changing.

11.2 Identification of Research Gap

Few studies have looked at the intersection of consumer perception, health, and sustainable packaging, especially in the Indian setting employing materials derived from agricultural waste. Health perception as a factor influencing acceptability of biodegradable packaging has not received as much attention as environmental perception. It is necessary to look into how consumers' perceptions of the health concerns associated with conventional packaging affect their adoption of sustainable packaging made from agricultural waste, as well as how eco-labels and green marketing affect consumers' awareness of health issues. The current study is based on this gap.

References

1. Atta-Delgado, M. X., Velazquez, G., Welti-Chanes, J., & Torres, J. A. (2024). Assessing consumer perceptions of sustainable packaging solutions. *International Journal of Food Science & Technology*.
2. Berthold, A., Guion, S., & Siegrist, M. (2024). The influence of material and colour of food packaging on consumers' perception and consumption willingness. *Food Humanities*, 2, Article 100265.
3. Central Pollution Control Board. (2024). *Annual report 2022–23: Plastic waste management*. Ministry of Environment, Forest and Climate Change, Government of India.
4. Duarte, P., Silva, S. C., Roza, A. S., & Dias, J. C. (2024). Enhancing consumer purchase intentions for sustainable packaging products: An in-depth analysis of key determinants and strategic insights. *Sustainable Futures*, 7, Article 100193.

5. Du Rietz, S., & Kremel, A. (2024). Consumer behaviour as a challenge and opportunity for circular food packaging—A systematic literature review. *Circular Economy and Sustainability*, 4, 413–438.
6. Horsthuis, E., Groenen, F., Toxopeus, M., & Lutters, E. (2024). Closing the perception-reality gap for sustainable fresh food plastic packaging. *Procedia CIRP*, 122, 647–652.
7. Kozik-Kołodziej, N. (2026). Consumer attitudes and perceptions toward sustainable packaging: A systematic literature review. *Sustainability*, 18(3), Article 1235.
8. Lin, J., Jaiswal, A. K., & Jaiswal, S. (2025). A critical review of consumer perception and environmental impacts of bioplastics in sustainable food packaging. *Sustainability*, 17(4), Article 1358.
9. Ministry of Environment, Forest and Climate Change. (2024). *Plastic waste management under the Plastic Waste Management Rules*. Government of India.
10. Ministry of Environment, Forest and Climate Change. (2024). *Plastic waste in the country*. Press Information Bureau, Government of India.
11. Food Safety and Standards Authority of India. (2024). *FSSAI launches project to address microplastic contamination in Indian food*. Ministry of Health and Family Welfare, Government of India.
12. Hussain, S., Akhter, R., & Maktedar, S. S. (2024). Advancements in sustainable food packaging: From eco-friendly materials to innovative technologies. *Sustainable Food Technology*, 2, 1297–1364.

PARENT-ADOLESCENT COMMUNICATION AND PROBLEMATIC DIGITAL BEHAVIORS AMONG ADOLESCENTS

Angeline Bhaskar Busi¹ and P. Mary Anupama²

INDLAS Hospitals, NTR University of Health Sciences, Vijayawada

Department of Biochemistry, St Joseph's College for Women, Visakhapatnam

Abstract

The rapid expansion of digital technology has reshaped adolescent leisure, social interaction, and developmental pathways in India, particularly in Andhra Pradesh. This chapter examines the associations between parent-adolescent communication, Internet Gaming Disorder (IGD), and smartphone addiction among 293 adolescents and young adults aged 14-21 years. Standardized instruments (Parent-Adolescent Communication Scale, IGDS9-SF, and SAS-SV) were administered. Results indicated that greater communicative openness was linked to lower levels of both IGD and smartphone addiction, whereas higher communication problems predicted elevated scores on both outcomes. Age differences emerged for smartphone addiction (higher among 18-21-year-olds), and gender differences appeared for IGD (higher in males) and openness (higher in females). Multiple regression analyses confirmed that communication problems explained substantial variance in both digital problems. The findings underscore the protective value of open, low-conflict family dialogue and highlight the need for culturally sensitive, parent-focused interventions to mitigate digital behavioral risks among South Indian youth.

Keywords: Parent-Adolescent Communication; Internet Gaming Disorder; Smartphone Addiction; Adolescents; Andhra Pradesh; Family Factors.

1. Introduction

Smartphones and online gaming have become central features of adolescent life in India. In Andhra Pradesh, rising internet penetration intersects with traditional family systems and accelerating urbanization, producing distinctive developmental pressures. Adolescents, defined by the World Health Organization as individuals aged 10-19 years (with middle and late subgroups spanning approximately 14-21 years), navigate rapid physical, emotional, cognitive, and social changes. These transitions increase vulnerability to peer influence, academic stress, and technology overuse, making parental guidance and open communication especially critical for psychological well-being and adaptive technology use.

Internet Gaming Disorder (IGD), listed in the DSM-5 as a condition requiring further research, is characterized by impaired control over gaming, interference with personal, family, social, educational, or occupational functioning, and persistence despite adverse consequences. Indian prevalence estimates range from 0.6% in some Northeast samples to 15.8% in certain high-school groups, with consistently higher rates among males and those reporting longer gaming

duration. Smartphone addiction, commonly assessed with the Smartphone Addiction Scale-Short Version (SAS-SV), shows even higher rates in South Indian samples, frequently exceeding 30-40% and reaching 39.9-68.7% among students. Drivers include nocturnal use, intensive social-media engagement, and academic pressure. The COVID-19 pandemic further intensified these risks by expanding online learning and reducing in-person social contact, blurring recreational and compulsive use.

Parent-adolescent communication and related family processes are widely recognized as protective or risk factors for digital behavioral problems. Open, trusting communication supports emotional regulation and reduces reliance on digital platforms for coping, whereas conflictual or emotionally invalidating exchanges increase distress and technology dependence. Although parenting styles, family structure, parental literacy, income, and screen-time norms also shape risk, the specific interplay of communication quality with both IGD and smartphone addiction remains comparatively under-examined in the Indian context. This chapter therefore investigates age- and gender-related differences, the associations among communication dimensions and the two digital outcomes, and the predictive contribution of communication to each outcome in an Andhra Pradesh sample of adolescents and young adults.

2. Review of Literature

2.1 Prevalence and Correlates of Digital Addictions

Meta-analyses estimate global adolescent IGD prevalence between 6.7% and 8.6%, with Asian rates reaching approximately 11.7%. Smartphone addiction affects roughly 20-30% of youth worldwide and co-occurs with IGD in 9-15% of cases. Within India, IGD rates vary from 0.6% among Northeast adolescents to 3.4-5.3% in Tamil Nadu and Gujarat samples and as high as 18.8% in some young-adult populations. Smartphone addiction is more prevalent: figures of 39.9% among Kerala college students, 40.9% among Visakhapatnam school adolescents, and 39.9-68.7% across broader South Indian regions have been reported. Both conditions are associated with elevated depression, anxiety, sleep disturbance, reduced academic performance, and diminished productivity. India's Economic Survey has also recognized the hazards of excessive digital engagement for youth well-being, noting average daily screen times exceeding five hours and substantial rates of problematic usage.

2.2 Parent-Adolescent Communication and Digital Risk

Open and supportive parent-adolescent communication functions as a protective factor by providing emotional-regulation outlets and heightening awareness of digital risks. Meta-analytic evidence indicates modest but consistent negative correlations between positive communication and problematic internet use ($r \approx -0.10$ to -0.20). Family-based interventions that improve communication have demonstrated reductions in risk of 20-30%. Conversely, problematic communication-characterized by frequent conflict, criticism, or emotional invalidation, predicts higher addiction severity ($r \approx 0.15$ - 0.30). Parental technoference (for example, phubbing) shows

a pooled positive association with children's problematic media use ($r \approx 0.30$), an effect that is stronger when both parents engage in such behavior and is partly mediated by interpersonal tension. In Indian families, open communication is inversely associated with both IGD and smartphone-addiction scores; however, hierarchical power dynamics, rural–urban differences, and time constraints in dual-earner households can limit communicative openness and elevate risk.

2.3 Parenting Styles and Family Context

Authoritative parenting high warmth combined with reasonable control and monitoring, is consistently linked to lower digital-addiction risk across cultures, including Indian samples. Authoritarian (high control, low warmth), permissive (high warmth, low control), and neglectful styles are associated with elevated risk, mediated in part by impulsivity, aggression, and poorer self-regulation. Systematic reviews suggest that low parental affection and high conflict can increase risk by up to 40%. In South Indian studies, non-authoritative styles raise the odds of smartphone addiction (adjusted odds ratios 1.5-3.3), whereas authoritative parenting reduces them (AOR ≈ 0.5). Additional contextual factors further moderate risk: joint-family supervision tends to be protective relative to nuclear arrangements; marital stability buffers against neglectful patterns; higher parental literacy and adequate income facilitate monitoring and reduce economic stress that might otherwise drive digital escapism; and excessive daily screen time (>4 hours) is a direct risk factor that is attenuated by active familial monitoring. Parental substance use and affective disorders also elevate intergenerational vulnerability.

2.4 Research Gap

Despite expanding literature on digital addictions, the joint influence of communication quality, demographic factors, and both IGD and smartphone addiction remains relatively underexplored in the Indian, and specifically Andhra Pradesh, context. Prior work has often examined isolated associations. The present study addresses this gap by examining age and gender differences, interrelations among communication dimensions and the two digital outcomes, and the predictive contribution of communication in a single South Indian adolescent sample.

3. Method

3.1 Sample and Procedure

A cross-sectional survey was conducted with 293 adolescents and young adults recruited through random sampling in Andhra Pradesh. The sample comprised 120 participants aged 14-17 years (41.0%) and 173 aged 18-21 years (59.0%); 167 were male (57.0%) and 126 female (43.0%). Anonymity was assured throughout, and institutional permissions and ethical clearances were obtained prior to data collection.

3.2 Measures

A demographic sheet recorded age, gender, education, area of residence, parental literacy, and parental monthly income. The Parent-Adolescent Communication Scale (PACS; Barnes &

Olson, 1982) assessed degree of openness and extent of problems on 5-point Likert items; higher scores indicate greater openness or greater communication problems, respectively. The Internet Gaming Disorder Scale-Short-Form (IGDS9-SF; Pontes & Griffiths, 2015), based on DSM-5 criteria, contains nine items rated from 1 (never) to 5 (very often); higher scores reflect greater IGD severity. The Smartphone Addiction Scale–Short Version (SAS-SV; Kwon *et al.*, 2013) is a 10-item measure of compulsive smartphone use, withdrawal, tolerance, and functional interference (Cronbach’s $\alpha = .91$). All instruments have demonstrated adequate reliability and validity in prior research.

3.3 Statistical Analysis

Analyses were performed with SPSS version 27. Descriptive statistics were generated for all study variables. Independent-samples t-tests compared age and gender groups on communication dimensions, IGD, and smartphone addiction. Pearson product-moment correlations examined associations among the variables. Multiple linear regression analyses tested the predictive contribution of age or gender together with each communication dimension to smartphone addiction and IGD. The significance level for all tests was set at $p < .05$.

4. Results

4.1 Age-Group Differences

Independent-samples t-tests revealed no significant differences between the 14-17 and 18-21 age groups on degree of openness, extent of problems, or IGD. Smartphone addiction scores were significantly higher among 18-21-year-olds ($M = 33.44$, $SD = 10.96$) than among 14-17-year-olds ($M = 29.31$, $SD = 11.36$), $t(291) = -3.13$, $p = .002$, Cohen’s $d = -0.37$, indicating a small-to-moderate effect.

Table 1: Age-group differences in parent-adolescent communication, internet gaming disorder, and smartphone addiction

Variable	Age Group	n	M	SD	t	p	Cohen’s d
Degree of Openness	14-17 yrs	120	37.91	9.59	0.58	.561	0.07
	18-21 yrs	173	37.21	10.35			
Extent of Problems	14-17 yrs	120	28.23	9.61	-1.12	.264	-0.13
	18-21 yrs	173	29.53	9.92			
Internet Gaming Disorder	14-17 yrs	120	19.68	10.17	-1.64	.102	-0.20
	18-21 yrs	173	21.66	10.25			
Smartphone Addiction	14-17 yrs	120	29.31	11.36	-3.13	.002**	-0.37
	18-21 yrs	173	33.44	10.96			

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

4.2 Gender Differences

Females scored significantly higher on degree of openness ($M = 39.53$, $SD = 9.76$) than males ($M = 35.96$, $SD = 9.99$), $t(291) = -3.06$, $p = .002$, $d = -0.36$. Males reported significantly higher IGD scores ($M = 22.64$, $SD = 10.28$) than females ($M = 18.48$, $SD = 9.73$), $t(291) = 3.51$, $p = .001$, $d = 0.41$. No significant gender differences were observed for extent of problems or smartphone addiction.

Table 2: Gender differences in parent-adolescent communication, internet gaming disorder, and smartphone addiction

Variable	Gender	n	M	SD	t	p	Cohen's d
Degree of Openness	Male	167	35.96	9.99	-3.06	.002**	-0.36
	Female	126	39.53	9.76			
Extent of Problems	Male	167	29.24	10.49	0.50	.621	0.06
	Female	126	28.67	8.84			
Internet Gaming Disorder	Male	167	22.64	10.28	3.51	.001**	0.41
	Female	126	18.48	9.73			
Smartphone Addiction	Male	167	31.53	11.22	-0.38	.701	-0.05
	Female	126	32.04	11.42			

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

4.3 Correlations

Degree of openness correlated negatively with extent of problems ($r = -.577$), IGD ($r = -.666$), and smartphone addiction ($r = -.325$), all $p < .01$. Extent of problems showed strong positive associations with IGD ($r = .761$) and smartphone addiction ($r = .582$). IGD and smartphone addiction were positively interrelated ($r = .574$). These patterns indicate that greater openness is linked to lower digital-problem scores, whereas higher communication problems co-occur with elevated addiction severity.

Table 3: Pearson correlations among parent-adolescent communication, internet gaming disorder, and smartphone addiction

Variable	1	2	3
1. Degree of Openness	-		
2. Extent of Problems	-.577**	-	
3. Internet Gaming Disorder	-.666**	.761**	-
4. Smartphone Addiction	-.325**	.582**	.574**

Note. ** Correlation is significant at the 0.01 level (2-tailed).

4.4 Multiple Regression Analyses

Two multiple-regression models predicted smartphone addiction. In Model 1, age and degree of openness jointly explained 13.5% of the variance ($R^2 = .135$, $F = 22.54$, $p < .001$). Age was a positive predictor ($\beta = .17$, $p < .01$) and openness a negative predictor ($\beta = -.32$, $p < .001$). In Model 2, age and extent of problems explained 35.9% of the variance ($R^2 = .359$, $F = 81.35$, $p < .001$); both age ($\beta = .14$, $p < .01$) and communication problems ($\beta = .57$, $p < .001$) were significant positive predictors. Model 2 accounted for substantially more variance than Model 1.

Table 4: Multiple regression models predicting smartphone addiction from age and parent-adolescent communication

Predictor	B	SE	β	t	B	SE	β	t
	Model 1: Age + Openness			Model 2: Age + Problems				
Constant	39.06	3.16		12.36	7.40	2.31		3.20
Age	3.88	1.25	.17**	3.10	3.27	1.08	.14**	3.03
Degree of Openness	-0.36	0.06	-.32***	-5.85	-	-	-	-
Extent of Problems	-	-	-	-	0.66	0.05	.57***	12.16
R^2 / Adjusted R^2	.135 / .129			.359 / .355				
F	22.54***			81.35***				

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

Two models also predicted IGD. Gender and degree of openness together explained 45.1% of the variance ($R^2 = .451$, $F = 119.28$, $p < .001$); openness was a strong negative predictor ($\beta = -.65$, $p < .001$), while gender was non-significant. Gender and extent of problems explained 61.1% of the variance ($R^2 = .611$, $F = 228.19$, $p < .001$). Communication problems were a strong positive predictor ($\beta = .76$, $p < .001$), and gender was significant ($\beta = -.18$, $p < .001$), indicating lower IGD scores among females. Model 2 again accounted for more variance than Model 1.

Table 5: Multiple regression models predicting internet gaming disorder from gender and parent-adolescent communication

Predictor	B	SE	β	t	B	SE	β	t
	Model 1: Gender + Openness			Model 2: Gender + Problems				
Constant	48.34	2.00		24.21	3.25	1.62		2.01
Gender	-1.79	0.91	-.09	-1.96	-3.71	0.76	-.18***	-4.91
Degree of Openness	-0.67	0.05	-.65** *	-14.73	-	-	-	-
Extent of Problems	-	-	-	-	0.79	0.04	.76***	20.64
R ² / Adjusted R ²	.451 / .448			.611 / .609				
F	119.28***			228.19***				

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. Gender coded such that negative β indicates lower IGD among females.

5. Discussion

The present findings partially supported age-group differences. Smartphone addiction was higher in the 18-21-year group, consistent with the increased autonomy, device ownership, academic demands, and broader social networks that characterize emerging adulthood. The absence of age differences in IGD and communication dimensions suggests relative stability of gaming patterns and family communication across this developmental window, or the buffering influence of parental factors that operate similarly for both age groups.

Gender differences were also partial. Higher IGD scores among males align with extensive Indian and international evidence linking competitive, achievement-oriented gaming preferences more strongly to male adolescents. Greater communicative openness among females may reflect socialization patterns that encourage relational disclosure within the family. The lack of gender difference in smartphone addiction is consistent with South Indian reports indicating comparable problematic smartphone use once social-media and communication functions are taken into account.

The correlational and regression results underscore the centrality of parent-adolescent communication. Openness showed consistent negative associations with both digital outcomes,

supporting its protective role. Communication problems, however, demonstrated stronger positive links and explained substantially more variance in both IGD and smartphone addiction. This pattern suggests that the presence of conflict, criticism, or emotional invalidation may be a more potent risk factor than the mere absence of openness. Reducing negative interaction patterns may therefore yield greater preventive benefit than solely promoting openness. The findings are congruent with prior work emphasizing family communication as a critical predictor of technology-related difficulties in Indian adolescents.

Practical implications are clear for South Indian families experiencing urbanization and dual-income transitions. Parent-focused programs that emphasize constructive conflict resolution, emotional validation, and consistent parental availability may help curb rising digital behavioral risks. Gender-sensitive approaches are warranted: interventions for boys may place greater emphasis on monitoring gaming involvement and providing alternative achievement outlets, while programs for girls can build on existing communicative strengths. Broader policy initiatives promoting safer online environments for children and adolescents in Andhra Pradesh can usefully incorporate family-communication components.

5.1 Limitations and Future Directions

The cross-sectional design precludes causal inferences about the direction of associations between communication and digital problems. Reliance on self-report measures introduces potential social-desirability and common-method bias. Although demographic information was collected, family-level variables such as parenting style were not assessed, limiting the ability to situate communication within broader parenting contexts. Future research should employ longitudinal designs, multi-informant assessments, and experimental or quasi-experimental interventions that actively modify communication quality. Studies that examine the moderating roles of family structure, parental literacy, income, and screen-time norms across diverse Indian regions would further strengthen the evidence base.

Conclusion

Parent-adolescent communication is meaningfully related to both Internet Gaming Disorder and smartphone addiction among South Indian adolescents and young adults. Higher degree of openness and lower extent of communication problems are associated with reduced digital risk. Age differences appear primarily for smartphone addiction, and gender differences primarily for IGD and openness. Communication problems emerge as particularly strong predictors of both outcomes. Culturally informed interventions that strengthen open dialogue and, especially, reduce familial conflict offer a promising pathway to support adolescent mental health and adaptive technology use in India's digital age.

References

1. American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). <https://doi.org/10.1176/appi.books.9780890425596>
2. Arnett, J. J. (2000). Emerging adulthood: A theory of development from the late teens through the twenties. *American Psychologist*, 55(5), 469–480.
3. Barnes, H. L., & Olson, D. H. (1982). Parent-adolescent communication scale. In D. H. Olson *et al.* (Eds.), *Family inventories* (pp. 33–48). University of Minnesota.
4. Chadda, R. K., & Deb, K. S. (2013). Indian family systems, collectivistic society and psychotherapy. *Indian Journal of Psychiatry*, 55(Suppl. 2), S299–S309.
5. Kerr, M., & Stattin, H. (2000). What parents know, how they know it, and several forms of adolescent adjustment. *Developmental Psychology*, 36(3), 366–380.
6. Kwon, M., Kim, D. J., Cho, H., & Yang, S. (2013). The smartphone addiction scale: Development and validation of a short version for adolescents. *PLOS ONE*, 8(12), Article e83558.
7. Lukavská, K., Hrabec, O., Lukavský, J., Demetrovics, Z., & Király, O. (2020). The associations between problem gaming, problematic internet use and parenting styles: A meta-analysis. *Addictive Behaviors*, 111, Article 106562.
8. Pontes, H. M., & Griffiths, M. D. (2015). Measuring DSM-5 Internet Gaming Disorder: Development and validation of a short psychometric scale. *Computers in Human Behavior*, 45, 137–143.
9. Twenge, J. M., & Campbell, W. K. (2018). Associations between screen time and lower psychological well-being among children and adolescents. *Preventive Medicine Reports*, 12, 271–283.
10. Yogesh, M., Ladani, H., & Parmar, D. (2024). Associations between smartphone addiction, parenting styles, and mental well-being among adolescents aged 15–19 years in Gujarat, India. *BMC Public Health*, 24, Article 2462.

FROM CLIMATE CRISIS TO HEALTH CRISIS: THE URGENT NEED FOR SUSTAINABLE ACTION

Manasa Panduranga

Department of Biotechnology, St. Joseph's College for Women (A), Visakhapatnam

Corresponding author E-mail: manasap2508@gmail.com

Abstract

Climate change is currently one of the most threatening factors in human health in the current century. Increased temperatures, extreme weather events, air pollution, loss of biodiversity, and alterations in the distribution of diseases have made environmental issues one of the greatest public health concerns. In this chapter, the connection between climate change, environmental sustainability, and human health will be considered. The impact of climate factors on human health through the increase in morbidity rates from heat stress, respiratory diseases, cardiovascular diseases, infectious diseases, food and water shortages, undernutrition, and mental disorders will be described. Special attention will be paid to vulnerable groups, including children, the elderly, and the poor. Sustainable measures for solving the aforementioned problems will be provided, including renewable energy generation, climate-compatible healthcare services, conservation of biodiversity, sustainable food production, resilient urban planning, and community-based strategies for decreasing health risks. In addition, special emphasis will be placed on the idea of planetary health as the necessity to protect the environment and save it in order to ensure the health of humans.

Keywords: Climate Change, Public Health, Sustainability, Air Pollution, Planetary Health, Climate Resilience.

1. Introduction

Climate change is no longer an environmental problem but is a major global public health problem of the 21st century. Rapid changes in climate occur due to the increase in the amount of greenhouse gases in the Earth's atmosphere, mainly because of anthropogenic activities. The burning of fossil fuels, such as coal, petroleum, and natural gas, deforestation, intensive industrialization, agricultural practices, transport, and unsustainable consumption patterns have greatly contributed to the rise in greenhouse gas emissions. These gases prevent heat from escaping the atmosphere, leading to global warming and changes in climate conditions.

The effects of climate change are much more complex than increased temperatures alone. Extreme weather events, including heat waves, floods, droughts, cyclones, and wildfires, have a significant impact on populations worldwide. Temperature and precipitation changes can alter ecosystems, influence agricultural production, decrease the availability of water, affect

biodiversity, and lead to the increased spread of infections. Natural systems are becoming increasingly stressed, and the resources necessary for human survival and health, such as clean air, safe drinking water, healthy food, and secure housing, are at risk.

Climate change influences human health directly and indirectly. In particular, the **direct** impact of global warming is connected with illnesses and deaths from heat, dehydration, respiration, injury, and death as a result of natural disasters. Indirect impact occurs when climate change modifies environmental and social circumstances. For example, changes in temperature and precipitation can affect the distribution of mosquitoes, which leads to the spread of diseases such as malaria or dengue fever. Moreover, the lack of rain and flooding influence food supply and water resources and cause the spread of malnutrition and waterborne illnesses.

The impact of climate change on people's health depends on certain factors. Certain groups of the population are particularly vulnerable to the influence of climate change, such as children, elderly people, poor communities, outdoor workers, and those who live in areas that are highly exposed to climate hazards. Moreover, communities that lack access to the healthcare system, safe water, proper sanitation, food, and adequate housing cannot easily adapt to environmental changes. In this way, it is obvious that climate change is closely connected to social inequality, environmental justice, and sustainable development.

Thus, climate change is not only a problem of the planet but also influences the health and well-being of the population. To protect public health, certain actions should be undertaken, including environmental protection, healthcare systems, sustainable development, and adaptation and mitigation of greenhouse gases. Thus, it is necessary to fight climate change itself and prepare the community for its unavoidable impact.

2. Climate Change and Human Health

Climate change influences human health through various interconnected pathways. Rising temperatures, changing precipitation patterns, extreme weather events, air pollution, and ecosystem changes lead to an increase in the risk of diseases, injuries, malnutrition, and mental health issues. Certain health impacts occur immediately, and some appear gradually due to changes in environmental and social circumstances. The main impacts on human health include:

2.1 Heat-Related Illnesses and Deaths

One of the direct impacts of climate change is the increase in the number of heat waves because of rising temperatures. Such exposure leads to an additional burden on the human body, especially on the cardiovascular and respiratory systems. Heat-related illnesses include heat exhaustion, dehydration, heat cramps, and heat stroke. Heat stroke may lead to organ damage and can be fatal if there is no proper medical treatment.

2.2 Respiratory Diseases and Air Pollution

There is a connection between climate change and air pollution. Coal, oil, and natural gas burning produces greenhouse gases together with pollutants that are harmful to respiratory organs. Climate change can contribute to the creation of ground level ozone and

2.3 Cardiovascular Diseases

High temperatures and air pollution can cause cardiovascular problems. High temperatures put extra strain on the circulatory system because the body requires more blood flow. Heat waves can lead to dehydration and electrolyte loss, which in turn increases stress on the heart.

2.4 Spread of Vector-Borne Diseases

The distribution, number, and activity of vectors, which transmit the disease, are all affected by climate change. Mosquitoes, ticks, and other vectors are affected by temperature, precipitation, humidity, and the availability of suitable habitats.

Vector-borne diseases, such as dengue and malaria, are impacted by environmental changes. Warmer temperatures may allow mosquitoes to live and breed in locations where they did not before, and changes in precipitation may provide additional breeding grounds. Extreme precipitation and floods create suitable breeding conditions due to stagnant water.

2.5 Water- and Food-Borne Diseases

Environmental changes and extreme events can have a strong impact on the safety of water and food. Heavy precipitation may contaminate sources of drinking water with sewage, microorganisms, chemicals, and other contaminants. It leads to an increased risk of water-borne diseases like cholera and diarrhoeal diseases.

2.6 Overall Health Burden

The health impacts of climate change are intertwined with each other. For example, a heat wave can aggravate heart disease and respiratory problems, whereas a flood can simultaneously lead to injuries, displacement of the population, water contamination, and increased susceptibility to infectious diseases. Crop losses due to drought can result in poor nutrition, which in turn might impair the capacity of the population to endure other health stressors.

Therefore, climate change can pose greater burdens on the healthcare system and exacerbate health problems in disadvantaged groups. Knowledge of such interconnections is crucial for climate adaptation planning and mitigation of the adverse effects on public health.

3. Environmental Challenges Driving the Health Crisis

Climate change is related to many environmental issues that directly or indirectly affect human health. Some of these include increased temperatures, air pollution, loss of biodiversity, and water and food insecurity. These issues are closely intertwined and interact with each other, increasing the vulnerability of people.

3.1 Rising Temperatures

The rise in temperature is one of the most obvious manifestations of the effects of climate change. The occurrence of extreme heat events and heatwaves can be harmful to human health. Under conditions of exposure to high temperatures, the human body loses water and electrolytes via sweating, and thus becomes prone to dehydration, heat exhaustion, and heat stroke. In the case of severe heatstroke, organ damage can occur, and it can even lead to death.

3.2 Air Pollution

Another important environmental factor that affects health is air pollution. Climate-related phenomena and human activities such as the burning of fossil fuels, industrialization, transportation, and biomass burning produce numerous pollutants in the atmosphere. Among them are fine particulate matter (PM_{2.5}), ground-level ozone, nitrogen oxide, sulfur dioxide, and other toxic substances.

3.3 Biodiversity Loss

The diversity of living organisms includes all the different kinds of living species on Earth along with the ecological systems in which they live. Climate change, deforestation, destruction of habitats, pollution, unsustainable use of natural resources, and changes in land use have resulted in a rapid reduction in biodiversity.

Ecosystems perform functions such as providing clean water, producing food, pollinating, fertilizing the soil, carbon storage, and controlling diseases. The functions of ecosystems can be affected by reducing their diversity. Changes in ecosystems can also lead to changes in the relationships between wild and domesticated animals, vectors, and people.

3.4 Water and Food Insecurity

Water scarcity occurs when the community does not have enough safe water at hand. If drought occurs, there will not be enough water available for consumption, sanitation, and agriculture. At the same time, floods will lead to contamination of freshwater sources with sewage, chemical substances, and disease-causing microorganisms. Consequently, the risk of diarrhea and other diseases caused by water will be higher.

Food insecurity appears if there are any climate-related events that affect the production and distribution of food supplies. Crop failures, falling agricultural productivity, and increasing food prices make it difficult for people to obtain nutritious food, especially if they belong to poor families. Food insecurity can cause malnutrition, deficiencies in micronutrients, child underdevelopment, and weakening of the immune system.

4. Sustainable Solution for Better Health

Solutions to both climate change and its health impacts include clean energy, climate-smart healthcare, sustainable food production, biodiversity conservation, and resilient cities. Renewable energy sources help decrease greenhouse gases and pollution. Energy-efficient

healthcare facilities and appropriate waste management make healthcare systems sustainable. Plant-based diets, decrease in the amount of food waste, and climate-resilient agriculture contribute to food security and nutrition. Biodiversity preservation includes forest, wetland, and wildlife protection, which helps maintain the balance of ecosystems and prevent the appearance of new diseases.

Table 1: Several Solutions for Sustainable Health

Solution	Key Actions	Health & Environmental Benefits
5.1 Transition to Clean Energy	Promote solar, wind, and other renewable energy sources	Reduces greenhouse gases and air pollution, thereby lowering respiratory and cardiovascular risks.
5.2 Climate - Smart Healthcare	Energy-efficient hospitals, renewable energy, and sustainable waste management should be used.	It creates low-carbon, resilient healthcare systems and reduces environmental pollution.
5.3 Sustainable Food Systems	Promoting plant-rich diets, reducing food waste, and adopting climate-resilient farming are essential.	Improves nutrition and food security while reducing environmental impacts
5.4 Biodiversity Conservation	Protect forests, wetlands, wildlife, and other natural habitats.	It maintains ecosystem stability, supports clean resources, and helps reduce disease risk.
5.5 Resilient Cities	Expanding green spaces, improving public transport, and adopting sustainable urban planning are recommended.	It reduces heat and air pollution exposure while improving urban health and quality of life.

5. Future Perspectives

Combating the health effects of climate change will be impossible without integrating climate change mitigation efforts into public health care and development strategies. The collaborative efforts of governments, scientists, health care providers, educational establishments, industries, and communities can help develop necessary adaptation and mitigation strategies. Improving the capacity of health care systems, disease surveillance, conducting climate change education, and ensuring that vulnerable population groups are protected can assist communities in preparing for the future health effects of climate change. Increased public awareness and a sustainable lifestyle are crucial for creating healthy communities resilient to climate change.

Conclusion

Climate change has serious health implications, in addition to environmental ones. Higher temperatures, increased air pollution, loss of biodiversity, and occurrence of extreme weather events are aggravating the disease burden and putting strain on health care systems. Dealing with these problems calls for immediate action on the part of states to cut down the emissions of greenhouse gases and ensure the protection of ecosystems, health care systems, and development sustainability. Investments in alternative sources of energy production, sustainable food chains, biodiversity conservation, and climate-resilient communities will yield long-term benefits for people and the planet.

References

1. Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.
2. World Health Organization. (2023). *Climate change and health*. World Health Organization. This resource provides information on the major health risks that can arise due to climate change, including heat stress, air pollution, infectious diseases, food insecurity, and extreme weather events.
3. United Nations Environment Programme. (2023). *Emissions gap report 2023: Broken record—Temperatures hit new highs, yet world fails to cut emissions (again)*. United Nations Environment Programme.
4. Lancet Countdown. (2023). *The Lancet Countdown on health and climate change: The 2023 report*. *The Lancet*. The report explores the connection between climate change and human health and the health threats that have emerged due to changes in the environment.
5. National Aeronautics and Space Administration. (2024). *Global climate change: Vital signs of the planet*. This webpage contains scientific data about global temperatures, greenhouse gases, sea level, and other aspects of climate change.
6. World Meteorological Organization. (2023). *State of the global climate 2023*. World Meteorological Organization.
7. United Nations. (2023). *The sustainable development goals report 2023*. United Nations. The report emphasizes the linkages between climate change, environment, human health, and sustainable development.

UNDERSTANDING CLIMATE CHANGE THROUGH THE LENS OF PANCHA BHOOHAS OF THE HUMAN BODY: BREATH, FEVER, NUTRITION, INFECTION AND MIND

Karakavalasa Joshitha

St. Joseph's College for Women (A), India

Corresponding author E-mail: joshithakarakavalasa@gmail.com

Abstract

Climate change is increasingly experienced not only as an environmental problem but as a public-health challenge affecting the air people breathe, the food and water they depend on, the infections they encounter, the heat their bodies regulate, and the psychological environments in which they live. Indian philosophical thought offers a culturally rooted perspective through the *Pancha Bhoothas*—Vayu (air), Prithvi (earth), Jala (water), Agni (fire), and Akasha (space). This chapter proposes these five elements as a symbolic lens for understanding interconnected climate–health pathways. They are not presented as biomedical entities or physiological equivalents. Contemporary climate and public-health evidence is organised around five human-centred dimensions: breath, nutrition, water and infection, heat and thermoregulation, and mental and psychosocial well-being. Vayu provides a conceptual bridge to atmospheric change and respiratory health; Prithvi and Jala to food, nutrition, water security and infection ecology; Agni to environmental heat and thermoregulation; and Akasha to psychological and social well-being. These relationships demonstrate how climate hazards can cascade across multiple dimensions of health. Building on this interpretation, the chapter proposes the KAVACH framework—Know, Anticipate, Value, Adapt, Co-regenerate and Heal—as a conceptual pathway towards climate-resilient health. The framework does not replace scientific models; rather, it seeks to communicate planetary–human interconnectedness through a culturally meaningful vocabulary.

Keywords: Climate Change, Pancha Bhoothas, Climate and Health, KAVACH, Traditional Knowledge, Planetary Health, Mental Health, Health Resilience.

1. Introduction

Climate change is no longer experienced only through temperature records, graphs and projections. It is increasingly encountered through human breath, hunger, infection, heat and psychological distress. The World Health Organization (WHO) reports that 3.6 billion people already live in areas highly susceptible to climate change and estimates approximately 250,000 additional deaths annually between 2030 and 2050 from undernutrition, malaria, diarrhoea and heat stress alone [1]. Climate change also threatens essential conditions for health, including clean air, safe water, adequate food and secure living environments [1].

The Intergovernmental Panel on Climate Change (IPCC) emphasises that climate-related illnesses, malnutrition, mental-health impacts and displacement are interconnected and unevenly distributed according to exposure and vulnerability [2]. Climate hazards can also produce cascading and compounding risks, in which several health and social consequences occur simultaneously [2].

Against this background, Indian philosophical thought offers an alternative conceptual entry point. The *Pancha Bhoothas*—Vayu, Prithvi, Jala, Agni and Akasha—provide a culturally familiar vocabulary through which relationships between human beings and the natural world may be contemplated.

This chapter does not claim that the five elements constitute scientific explanations of climate change. Instead, it asks a different question:

What becomes visible when established climate–health evidence is viewed through a culturally rooted language of interconnected elements?

The central proposition is simple:

When the conditions that sustain life outside the body are destabilised, their consequences can eventually be experienced within the body and mind.

2. Pancha Bhoothas: From Cosmology to Climate–Health Interpretation

Verse 9 of the *Saundarya Lahari*, traditionally attributed to Adi Shankaracharya, describes an ascending symbolic arrangement involving earth, water, fire, air, space and mind:

महीं मूलाधारे कमपि मणिपूरे हुतवहं
स्थितं स्वाधिष्ठाने हृदि मरुतमाकाशमुपरि ।
मनोऽपि भ्रूमध्ये सकलमपि भित्त्वा कुलपथं
सहस्रारे पद्मे सह रहसि पत्या विहरसे ॥ ९ ॥

Table 1: Pancha Bhootha–Climate–Health Conceptual Matrix

Pancha Bhootha	Climate/Environmental Dimension	Human-Health Pathway
Vayu – Air	Smoke, particulate pollution, ozone, allergens	Breath → respiratory health
Prithvi – Earth	Soil degradation, drought, ecosystem disruption	Food → nutrition
Jala – Water	Floods, drought, contamination, water insecurity	Water → infection and security
Agni – Fire	Heatwaves, rising temperatures, thermal stress	Heat → thermoregulation
Akasha – Space	Displacement, uncertainty, social disruption	Mind → psychosocial well-being

For this chapter, the verse is used as a philosophical and symbolic reference, not as evidence for biomedical anatomy or climate science. Interpretations of Indian philosophical traditions are diverse; therefore, the present mapping should be understood as a contemporary conceptual construction.

The familiar philosophical expression *Yatha Pinde Tatha Brahmande*—the relationship between microcosm and macrocosm—provides a further conceptual basis for reflecting on human beings as embedded within the natural world.

3. Climate Change as an Interconnected Health Disturbance

Climate change does not operate through isolated hazards. Heat, air pollution, food insecurity, water stress, infectious diseases, displacement and psychological distress can interact and reinforce one another [2,3].

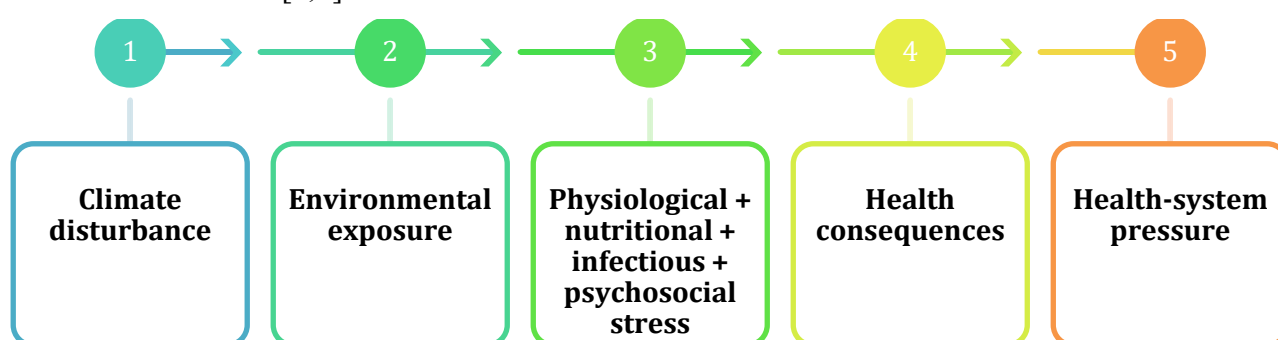


Figure 1: The Climate–Health Cascade

A heatwave, for example, may simultaneously increase physiological stress, worsen air quality, increase water demand and reduce work capacity. Flooding may contaminate water, damage healthcare facilities, disrupt food supplies, increase exposure to infectious diseases and displace communities [2].

The *Pancha Bhootha* interpretation therefore presents climate change as a whole-system disturbance rather than a collection of unrelated hazards.

4. Vayu: When Planetary Breath Enters the Human Lung

Breathing is one of the most immediate exchanges between the human body and its surroundings. Every inhalation brings the external atmosphere into biological space.

Climate change can interact with air quality through wildfire smoke, heat-related ozone formation, dust and changes in allergen exposure [2]. Wildfires are particularly important because smoke contains particulate matter and multiple gaseous pollutants. WHO reports that approximately 90% of the total particle mass emitted by wildfires consists of PM_{2.5}. [4]. Wildfire smoke can also travel considerable distances from its source [4].

Air pollution is therefore not simply an atmospheric concern. It becomes a respiratory and cardiovascular health concern.

Within this framework, Vayu, symbolically associated with air and movement, provides a culturally meaningful bridge between atmospheric conditions and human breathing.

Every breath connects the individual to the planet; the lung is therefore one place where planetary change becomes personal.

5. Prithvi–Jala: Nutrition, Water and the Ecology of Infection

Prithvi represents earth and the ecological foundations of nourishment, while *Jala* represents water and the conditions necessary for life.

Food begins not on the plate, but in soil, rainfall, seeds, biodiversity and agricultural ecosystems. Climate change and extreme weather can disrupt agricultural production, food availability and nutritional security [2,3]. Drought, flooding, changing rainfall patterns and heat stress may affect the ecological systems upon which food production depends.

The *Prithvi–Jala* relationship also provides a useful conceptual entry point into infection ecology. Flooding may contaminate water and disrupt sanitation, while drought can reduce water availability and increase dependence on unsafe sources. Changes in temperature and precipitation can also influence the distribution and seasonality of climate-sensitive infectious diseases [2,5].

The relationship can therefore be represented as:

Climate stress → ecosystem disruption → food/water insecurity → nutritional vulnerability and altered infection risk → health-system stress

The purpose of this cascade is not to claim that every climate event produces every health outcome, but to show how environmental systems can connect multiple pathways of vulnerability.

6. Agni: Heat, Fever and Climate Physiology

Agni provides perhaps the most striking symbolic connection between traditional thought and climate physiology.

A necessary scientific distinction must nevertheless be maintained: environmental heat and clinical fever are not the same physiological phenomenon. Fever is a regulated elevation of body temperature associated with endogenous inflammatory processes, whereas heat illness occurs when environmental and metabolic heat loads overwhelm the body's ability to dissipate heat.

WHO estimates that approximately 489,000 heat-related deaths occurred annually during 2000–2019, with 45% occurring in Asia. Heat-related mortality among adults aged 65 years and older increased by approximately 85% between 2000–2004 and 2017–2021 [3].

Extreme heat can contribute to heat exhaustion and heatstroke and can worsen underlying cardiovascular, respiratory, renal and other conditions [3].

Thus, *Agni* can be interpreted as a symbolic reminder of a fundamental physiological paradox:

Heat sustains life, yet becomes harmful when thermal load exceeds the body's capacity for regulation.

Climate change intensifies this challenge by increasing exposure to extreme heat, particularly among populations whose occupations, housing, socioeconomic circumstances or access to cooling increase vulnerability.

7. Akasha: The Invisible Climate of the Mind

Akasha represents the less visible spaces in which environmental change is experienced—the psychological, social and relational dimensions of human life.

A flood may destroy not only a house but also routines, livelihoods and social networks. A drought may threaten not only crops but also livelihood security and cultural continuity. Displacement may generate uncertainty and weaken established social connections.

The IPCC identifies mental-health and well-being impacts among important consequences of climate change and notes that these impacts vary according to exposure, vulnerability and social context [2]. Anxiety, stress, grief and trauma may arise following extreme events, while prolonged uncertainty can create additional psychological burdens.

However, climate-related psychological responses should not be reduced to illness alone. Social support, community cohesion, cultural practices and access to resources can strengthen resilience. In this framework, *Akasha* therefore serves as a metaphor for the psychological space in which ecological uncertainty is experienced.

8. Vulnerability, Challenges and Evidence Gaps

Climate change does not affect all populations equally. Children, older adults, pregnant women, people with disabilities, outdoor workers, people with chronic conditions and low-income communities may face greater exposure or reduced adaptive capacity [1,2].

The challenge extends beyond exposure itself. Health systems may face simultaneous demands from heat-related illness, infectious diseases, nutritional insecurity, displacement and psychological distress. Important gaps remain in climate-sensitive surveillance, early-warning systems, disaggregated health data, healthcare preparedness and coordination between environmental and health sectors [2,6].

Traditional and Indigenous knowledge may contribute valuable local perspectives, particularly in community engagement and adaptation. However, such knowledge should be approached respectfully and critically rather than being presented as automatically equivalent to scientific evidence.

A significant future research question is therefore:

Can culturally grounded frameworks improve climate-health understanding, communication and preparedness while maintaining scientific accuracy?

9. KAVACH: From Understanding to Resilience

The *Pancha Bhootha* perspective provides the conceptual foundation of this chapter. KAVACH translates that perspective into an action-oriented framework.

KAVACH is proposed by the author as a conceptual model, not as an established public-health intervention.

Table 2: The KAVACH Framework

Letter	Principle	Climate-Health Meaning
K	Know	Understand environmental–health connections
A	Anticipate	Identify risks before they become crises
V	Value	Recognise air, water, food, thermal comfort and psychological safety as health assets
A	Adapt	Strengthen individual, community and health-system capacity
C	Co-regenerate	Restore ecosystems, livelihoods and social resilience
H	Heal	Restore health, communities and human–environment relationships



Figure 2: KAVACH Pathway

The progression is deliberate. It moves from awareness to anticipation, anticipation to adaptation, and adaptation towards regeneration and healing.

KAVACH therefore shifts the idea of resilience beyond simply surviving repeated environmental shocks. It proposes that resilience should also involve protecting and regenerating the ecological and social foundations upon which health depends.

10. Conceptual Significance and Future Directions

The climate–health pathways described in this chapter are supported by established scientific evidence [1–6]. The originality of the present work lies not in proposing new biomedical mechanisms but in organising familiar climate-health relationships through a culturally rooted conceptual vocabulary.

The framework may have potential applications in climate-health education, community engagement, interdisciplinary research, culturally sensitive risk communication and health-system planning.

These possibilities remain to be tested. Future research could examine whether KAVACH improves climate-health literacy, risk perception, community participation, preparedness or

health-system resilience. Mixed-methods research involving public-health professionals, environmental scientists, social scientists, community representatives and scholars of Indian knowledge traditions could help evaluate the framework.

Conclusion

Climate change is increasingly expressed through the fundamental conditions of human health—the air we breathe, the food and water that sustain us, the heat our bodies regulate, and the psychological environments in which we live.

The *Pancha Bhoothas* provide a culturally rooted language for viewing these relationships as interconnected rather than isolated. Vayu connects atmospheric change with breath; Prithvi and Jala connect ecological foundations with nutrition, water and infection; Agni connects environmental heat with thermoregulation; and Akasha connects ecological disruption with psychological and social well-being.

These relationships form a larger climate–health cascade in which environmental disruption can move through bodies, communities, ecosystems and health systems.

From this perspective emerges KAVACH—Know, Anticipate, Value, Adapt, Co-regenerate and Heal—a proposed pathway from climate-health awareness towards resilience and regeneration.

KAVACH does not replace climate science with philosophy. It creates a bridge through which traditional knowledge and contemporary public health can illuminate a shared principle: human health is embedded within planetary health.

References

1. World Health Organization. (2023). *Climate change and health*. World Health Organization.
2. Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
3. World Health Organization. (2026). *Heat and health*. World Health Organization.
4. World Health Organization. (2026). *Wildfires and health*. World Health Organization.
5. Wu, X., Lu, Y., Zhou, S., Chen, L., & Xu, B. (2016). Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. *Environment International*, 86, 14–23. <https://doi.org/10.1016/j.envint.2015.09.007>
6. Romanello, M., Walawender, M., Hsu, S. C., Moskeland, A., Palmeiro-Silva, Y., Scamman, D., *et al.* (2024). The 2024 report of the Lancet Countdown on health and climate change: Facing record-breaking threats from delayed action. *The Lancet*, 404(10465), 1847–1896. [https://doi.org/10.1016/S0140-6736\(24\)01822-1](https://doi.org/10.1016/S0140-6736(24)01822-1)
7. Śaṅkarācārya. (1958). *The Saundaryalaharī or Flood of beauty* (W. N. Brown, Ed. & Trans.; Harvard Oriental Series, Vol. 43). Harvard University Press.

PLANT-DERIVED BIOACTIVE COMPOUNDS: FROM TRADITIONAL KNOWLEDGE TO NATURAL THERAPEUTIC DISCOVERY

Gundavarapu Bhargavi

Corresponding author E-mail: gbksree3@gmail.com

Abstract

Ayurveda, one of the earliest traditional systems of medicine, contains systematic knowledge of medicinal plants and their therapeutic applications, documented in the *Charaka Samhita*, attributed to the Ayurvedic scholar Charaka. Although these classical scriptures provide an understanding of the use of medicinal plants, the identification and characterization of the individual bioactive components remained largely unexplored, as the modern analytical approaches were not available at that time. Advancements in scientific methods including molecular biology, genomics, metabolomics, analytical chemistry, phytochemistry have opened new possibilities to discover and characterize the bioactive compounds in the medicinal plants. In addition, artificial intelligence (AI), omics data analysis and computational biology have accelerated the path of discovery from the identification of the candidate compound, prediction of their biological activities, exploration of the underlying molecular mechanisms and the therapeutic potential. However, there remains a substantial gap between the discovery and translation of a plant-derived bioactive compound into safe, standardized and clinically useful therapeutics. Factors such as limited bioavailability, challenges in standardization, batch-to-batch variation, pharmacokinetic properties, regulatory requirements and clinical validation limit the successful translation of a bioactive compound into therapeutics. This chapter highlights how integrating the traditional knowledge of medicinal plants with emerging scientific technologies could shed light on opportunities for advancing the traditional medicinal plant knowledge toward modern bioactive compound discovery and therapeutic development. It further critically examines the scientific, technological, regulatory, and translational barriers that influence the successful progression of these compounds from traditional use and laboratory discovery to clinically relevant therapeutics.

Keywords: Plant-Derived Bioactive Compounds, Natural Therapeutics, Metabolomics, Genomics, Bioavailability, Regulatory Requirements, Clinical Validation, Translational Challenges.

Introduction

The above figure illustrates how traditional medicinal-plant knowledge is progressed into their systematic discovery and development of plant-derived natural therapeutics. Traditional knowledge guides plant selection and therapeutic exploration, followed by extraction, metabolite

profiling, identification and characterization of bioactive constituents, biological and mechanistic validation, and subsequent standardization, formulation, and therapeutic development. Although advances in phytochemistry, analytical technologies, metabolomics, genomics, and computational tools are speeding up the discovery process, challenges related to chemical variability, bioavailability, pharmacokinetics, safety, and reproducibility contribute to the discovery-to-translation gap. Figure made using AI tool Figure guild.

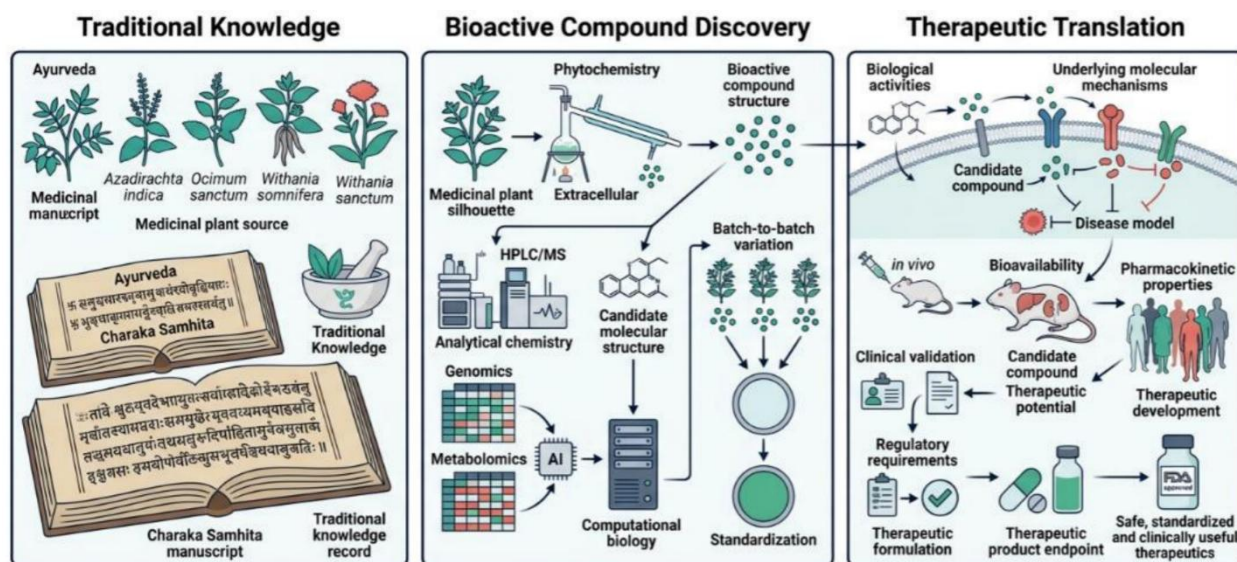


Figure 1: From traditional medicinal knowledge to natural therapeutic development

Table 1: Representative plant-derived bioactive metabolites and challenges in their therapeutic development

Therapeutic area or condition studied	Plant-derived metabolite or phytochemical preparation	Technique used for extraction / characterization	Major challenges faced	Reference
Malaria	Artemisinin – <i>Artemisia annua</i>	Solvent extraction; ultrasound-assisted or supercritical-fluid extraction; HPLC, LC–MS and NMR for characterization/quantification	Low and variable artemisinin content in plant material; extraction efficiency depends on processing conditions and plant material characteristics	Nahar <i>et al.</i> , 2020
Cancer	Paclitaxel – <i>Taxus</i> spp.	Solvent extraction; HPLC, LC–MS/MS and mass spectrometry for taxane profiling	Analytical characterization of taxanes	Kerns <i>et al.</i> , 1994

Hematological malignancies / leukemia	Vincristine – <i>Catharanthus roseus</i>	Solvent extraction; HPLC and LC–MS/MS for detection and quantification	Very low abundance, complex structure	Paul <i>et al.</i> , 2023
Type 2 diabetes / metabolic disorders	Berberine – <i>Berberis</i> spp. / <i>Coptis</i> spp.	Solvent extraction; HPLC, HPLC-DAD/PDA and UHPLC-Q-TOF-MS	Large variation in berberine content according to species and geographical origin	Neag <i>et al.</i> , 2018
Inflammatory disorders	Curcumin – <i>Curcuma longa</i>	Solvent/reflux extraction; ultrasound/subcritical -water extraction; HPLC and MS/MS for identification and quantification	Poor aqueous solubility, low bioavailability and instability; extraction yield varies with method and processing conditions	Li <i>et al.</i> , 2021; Abd El-Hack <i>et al.</i> , 2021
Cardiovascular diseases	Resveratrol – <i>Vitis vinifera</i> and other plants	Solvent, ultrasound-assisted or other extraction; HPLC/UHPLC, HPLC–MS/MS for identification and quantification	Strong dependence on plant variety and processing; instability to light, oxygen, pH and temperature; poor bioavailability and rapid metabolism	Căpruciu <i>et al.</i> , 2025; Goel <i>et al.</i> , 2025
Liver diseases / hepatic disorders	Silymarin (silybin and related flavonolignans) – <i>Silybum marianum</i>	Solvent extraction; TLC/HPTLC, HPLC/UHPLC and NMR for characterization	Silymarin is a mixture rather than a single compound; variability in commercial preparations and raw material; extraction efficiency and standardization remain challenging	Baba <i>et al.</i> , 2026

The table summarizes selected plant-derived metabolites or phytochemical preparation reported to exhibit biological activity against the condition studied, along with the extraction and characterization techniques used for their identification and the key challenges associated with their development as therapeutic candidates. The reported activities represent evidence from experimental and/or preclinical studies and should not necessarily be interpreted as established clinical efficacy

Representative Plant-Derived Bioactive Compounds and Challenges in Their Therapeutic Development

Representative examples of plant-derived bioactive compounds which progressed from natural-product research toward therapeutic applications across diverse conditions studied include: artemisinin from *Artemisia annua* for malaria; paclitaxel from *Taxus* spp. for cancer; vincristine from *Catharanthus roseus* for hematological malignancies; berberine from *Berberis* and *Coptis* spp. for metabolic disorders; curcumin from *Curcuma longa* for inflammatory conditions; resveratrol from *Vitis vinifera* and other plants for cardiovascular and other health applications and silymarin from *Silybum marianum* for hepatic disorders (Nahar *et al.*, 2020; Kerns *et al.*, 1994; Paul *et al.*, 2023; Neag *et al.*, 2018; Abd El-Hack *et al.*, 2021; Li *et al.*, 2021; Căpruciu *et al.*, 2025; Goel *et al.*, 2025; Baba *et al.*, 2026) (Table 1). These examples illustrate that identification of a biologically active plant metabolite represents only an initial stage of therapeutic development, with subsequent optimization of extraction and characterization, biological validation, standardization, formulation, and pharmacokinetic evaluation being important for advancing natural-product candidates toward reproducible and clinically relevant applications.

Regulatory and Translational Challenges

Unlike chemically derived drugs, plant derived preparations may contain several contaminants in varying concentrations. The translation of plant-derived bioactive compounds from laboratory discovery into clinically useful therapeutics is influenced not only by their biological activity but also by regulatory, manufacturing, safety, and clinical considerations. Variability creates challenges in establishing consistent composition, quality, purity, potency, and batch-to-batch reproducibility (WHO, 2003; FDA, 2016; EMA, 2022). Comprehensive knowledge of the medicinal plants, their characterization, optimization of the extraction and manufacturing procedures, appropriate quality-control, and identification of relevant chemical or biological markers are therefore important for ensuring reproducibility and regulatory compliance (WHO, 2003; FDA, 2016; EMA, 2022). When plant-derived products are intended for prolonged use or are administered alongside conventional medicines, there is a need for safety assessment which requires evaluation of toxicity, potential herb–drug interactions, contaminants, stability, and pharmacokinetic behaviour, particularly (WHO, 2021; EMA, 2022, 2024).

The way a drug is absorbed, its metabolism, its interactions, its concentrations in the bloodstream and its differed responses in different individuals can all change the results seen in patients. This shows that it's important to plan studies very carefully to evaluate the safety of the medicine, the dosage required and the reproducibility in its efficacy. Also, the rules that need to be followed can be different depending on whether the product's made as a purified natural compound / a

standardized botanical preparation / a traditional herbal medicine / a dietary product or a pharmaceutical drug (EMA, 2017).

Emerging Technologies and Future Perspectives

Emerging technologies such as advances in metabolomics, high-resolution mass spectrometry, genomics, transcriptomics, and proteomics are creating new opportunities to accelerate the discovery, characterization, and development of plant-derived therapeutics. Integration of multi-omics datasets with artificial intelligence (AI), machine learning (ML), and computational approaches helps in conducting comprehensive investigation of plant chemical diversity and the biological responses associated with bioactive metabolites. In addition, cheminformatics and molecular modelling support the prediction of pharmacological properties, toxicity, metabolism, and drug-like characteristics; advances in green extraction technologies, nanoformulation, targeted delivery systems, and precision analytical platforms may help overcome limitations associated with extraction efficiency, stability, solubility, and bioavailability. Therefore, the combination of traditional medicinal knowledge with advanced analytical, computational, biological, and pharmaceutical technologies may lead to development of natural therapeutics.

However, technological advances should be accompanied by rigorous experimental validation, standardized methodologies, reproducible datasets, safety assessment, and appropriate clinical evaluation. Establishing communication between cross-platform databases linking medicinal plants, metabolites, molecular targets, pharmacological activities, and clinical evidence could further strengthen the translation of traditional knowledge into scientifically validated therapeutics.

Therefore, interdisciplinary approaches combining ethnobotanical knowledge, modern omics technologies, computational prediction, experimental validation, formulation science, and regulatory frameworks may ultimately provide a more systematic pathway for advancing plant-derived bioactive compounds from discovery to safe, standardized, and clinically relevant natural therapeutics.

References

1. Abd El-Hack, M. E., El-Saadony, M. T., Swelum, A. A., Arif, M., Abo Ghanima, M. M., Shukry, M., ... El-Tarabily, K. A. (2021). Curcumin, the active substance of turmeric: Its effects on health and ways to improve its bioavailability. *Journal of the Science of Food and Agriculture*, 101(14), 5747–5762.
2. Baba, F. V., Khodadadi, M., Esfandiari, Z., & Ahranjani, P. J. (2026). *Silybum marianum* L. (milk thistle): A review of phytochemical and bioactive compound extraction, food applications, and safety considerations. *Applied Food Research*, Article 102099.
3. Brusotti, G., Cesari, I., Dentamaro, A., Caccialanza, G., & Massolini, G. (2014). Isolation and characterization of bioactive compounds from plant resources: The role of analysis in

- the ethnopharmacological approach. *Journal of Pharmaceutical and Biomedical Analysis*, 87, 218–228.
4. Căpruciu, R., & Gheorghiu, C. N. (2025). Methods for synthesis and extraction of resveratrol from grapevine: Challenges and advances in compound identification and analysis. *Foods*, 14(7), Article 1091.
5. Chele, K. H., Piater, L. A., van der Hooft, J. J., & Tugizimana, F. (2025). Bridging ethnobotanical knowledge and multi-omics approaches for plant-derived natural product discovery. *Metabolites*, 15(6), Article 362.
6. European Medicines Agency, Committee on Herbal Medicinal Products. (2017). *Guideline on the assessment of clinical safety and efficacy in the preparation of EU herbal monographs for well-established and traditional herbal medicinal products* (EMA/HMPC/104613/2005 Rev. 1). European Medicines Agency.
7. European Medicines Agency. (2022). *Final guideline on quality of herbal medicinal products/traditional herbal medicinal products—Revision 3* (EMA/HMPC/CHMP/CVMP/201116/2005 Rev. 3). European Medicines Agency.
8. European Medicines Agency, Committee on Herbal Medicinal Products. (2024). *Questions and answers on quality of herbal medicinal products/traditional herbal medicinal products—Revision 7* (EMA/HMPC/41500/2010 Rev. 7). European Medicines Agency.
9. U.S. Food and Drug Administration. (2016). *Botanical drug development: Guidance for industry*. Center for Drug Evaluation and Research, U.S. Food and Drug Administration.
10. Goel, H., Nagarajan, K., Nainwal, L. M., & Bhardwaj, S. (2025). Analytical techniques for the quantification and validation of resveratrol: A review. *Anti-Inflammatory & Anti-Allergy Agents in Medicinal Chemistry*.
11. Kim, H. K., Kim, S. J., Gil, W. J., & Yang, C. S. (2025). Exploring the therapeutic potential of phytochemicals: Challenges and strategies for clinical translation. *Phytomedicine*, Article 157090.
12. Kerns, E. H., Volk, K. J., Hill, S. E., & Lee, M. S. (1994). Profiling taxanes in *Taxus* extracts using LC/MS and LC/MS/MS techniques. *Journal of Natural Products*, 57(10), 1391–1403.
13. Latif, R., & Nawaz, T. (2026). Medicinal plants and human health: A comprehensive review of bioactive compounds, therapeutic effects, and applications. *Phytochemistry Reviews*, 25(3), 2299–2342.
14. Lautié, E., Russo, O., Ducrot, P., & Boutin, J. A. (2020). Unraveling plant natural chemical diversity for drug discovery purposes. *Frontiers in Pharmacology*, 11, Article 397.
15. Li, Y., Qaria, M. A., Sivasamy, S., Jianzhong, S., & Daochen, Z. (2021). Curcumin production and bioavailability: A comprehensive review of curcumin extraction, synthesis,

- biotransformation and delivery systems. *Industrial Crops and Products*, 172, Article 114050.
16. Nahar, L., Guo, M., & Sarker, S. D. (2020). A review on the latest advances in extraction and analysis of artemisinin. *Phytochemical Analysis*, 31(1), 5–14.
 17. Neag, M. A., Mocan, A., Echeverría, J., Pop, R. M., Bocsan, C. I., Crişan, G., & Buzoianu, A. D. (2018). Berberine: Botanical occurrence, traditional uses, extraction methods, and relevance in cardiovascular, metabolic, hepatic, and renal disorders. *Frontiers in Pharmacology*, 9, Article 557.
 18. Paul, A., Acharya, K., & Chakraborty, N. (2023). Biosynthesis, extraction, detection and pharmacological attributes of vinblastine and vincristine, two important chemotherapeutic alkaloids of *Catharanthus roseus* (L.) G. Don: A review. *South African Journal of Botany*, 161, 365–376.
 19. Ramesh, M. M., Dinesh, S., Venkatappa, A. H., & Lobo, R. (2026). Pharmacological complexities of herbal medicinal extracts: A review of bioavailability, interactions, and standardization. *Current Drug Metabolism*.
 20. Sorkin, B. C., Kuszak, A. J., Bloss, G., Fukagawa, N. K., Hoffman, F. A., Jafari, M., ... Pauli, G. F. (2019). Improving natural product research translation: From source to clinical trial. *FASEB Journal: Official Publication of the Federation of American Societies for Experimental Biology*, 34(1), 41.
 21. Varghese, R., Shringi, H., Efferth, T., & Ramamoorthy, S. (2025). Artificial intelligence-driven approaches in phytochemical research: Trends and prospects. *Phytochemistry Reviews*, 24(5), 3649–3664.
 22. World Health Organization. (2003). *WHO guidelines on good agricultural and collection practices (GACP) for medicinal plants*. World Health Organization.
 23. World Health Organization. (2021). *Key technical issues of herbal medicines with reference to interaction with other medicines* (ISBN 978-92-4-001914-0). World Health Organization.

CLIMATE ANXIETY AND PSYCHOLOGICAL RESILIENCE: UNDERSTANDING MENTAL HEALTH IN AN ERA OF ENVIRONMENTAL CHANGE

Shaista Bhartiya

Department of Psychology,

St. Joseph's College for Women (Autonomous), Visakhapatnam, Andhra Pradesh, India

Affiliation: Saroj International University, Lucknow, Uttar Pradesh, India

Corresponding author E-mail: arishazainab2015@gmail.com

Abstract

Climate change is increasingly recognized as a threat to psychological as well as physical health. Extreme weather events, environmental degradation, displacement, livelihood disruption, biodiversity loss, and uncertainty about the future can contribute to fear, worry, grief, anger, helplessness, and anxiety. Climate anxiety refers specifically to distress associated with climate change, while eco-anxiety, ecological grief, and solastalgia describe broader responses to environmental disruption. These responses should not automatically be treated as mental disorders because concern about genuine environmental threats may also support preparedness, environmental responsibility, and collective action. This chapter presents a narrative and comparative review of literature on climate anxiety, psychological well-being, coping, and resilience, with particular attention to young people and the Indian context. Evidence indicates a meaningful association between climate anxiety and poorer psychological well-being, although outcomes vary with coping strategies, environmental identity, perceived efficacy, social support, and exposure to climate-related hazards. Psychological resilience is therefore best understood not as the absence of distress but as the capacity to experience concern while maintaining adaptive functioning and meaningful action. Integrating climate literacy, emotional regulation, constructive hope, social connectedness, resilience-building, and accessible mental-health support into climate-health responses may help individuals and communities respond more adaptively to environmental uncertainty.

Keywords: Climate Anxiety, Eco-Anxiety, Psychological Resilience, Mental Health, Climate Change, Coping.

1. Introduction

Climate change has traditionally been discussed in terms of rising temperatures, extreme weather, biodiversity loss, food insecurity, and physical health consequences. Increasingly, it is also understood as a psychosocial challenge. The World Health Organization (WHO, 2022) notes that climate change can worsen social, environmental, and economic determinants of mental health and can contribute to emotional distress and other psychological difficulties. Climate-

related hazards may affect people directly through floods, cyclones, droughts, heatwaves, and other disasters, and indirectly through livelihood insecurity, displacement, food and water insecurity, environmental degradation, and disruption of social networks.

Psychological responses may also arise from awareness of environmental threats even when an individual has not personally experienced a disaster. This has contributed to growing interest in climate anxiety, eco-anxiety, ecological grief, and solastalgia. Ojala *et al.* (2021) emphasize that negative environmental emotions can be understandable responses to real threats and may sometimes support constructive engagement. The central psychological question is therefore not whether climate concern exists, but how that concern is interpreted, regulated, and translated into behaviour.

This chapter reviews major psychological concepts related to climate distress, the relationship between climate anxiety and well-being, coping and resilience mechanisms, the experiences of young people, and implications for India. It also considers practical directions for psychological and community-based responses.

2. Climate Anxiety and Related Environmental Distress

2.1 Climate anxiety, eco-anxiety and ecological grief

Climate anxiety is an emerging construct describing cognitive, emotional, behavioural, and functional responses associated with climate change. Clayton and Karazsia (2020), through the Climate Change Anxiety Scale, distinguished cognitive-emotional responses from functional impairment. Climate anxiety therefore differs from general anxiety in its specific focus on climate change, although the two may coexist. Boehme *et al.* (2024) note that the field is still developing, particularly with respect to mechanisms, measurement, and intervention.

Eco-anxiety is broader and may include distress related to climate change, biodiversity loss, pollution, ecological destruction, and resource depletion. Hogg *et al.* (2021) found that eco-anxiety is multidimensional, including affective symptoms, rumination, behavioural symptoms, and concerns about one's environmental impact. Ecological grief refers to sadness, mourning, anger, or helplessness associated with actual or anticipated environmental losses (Ojala *et al.*, 2021).

2.2 Solastalgia

Albrecht *et al.* (2007) introduced solastalgia to describe distress associated with environmental transformation while a person remains connected to the affected home environment. The concept is relevant to communities experiencing gradual landscape change, drought, pollution, coastal change, or ecological degradation. Together, these concepts show that environmental distress can range from ordinary concern to substantial impairment and should be understood on a continuum rather than automatically pathologized.

3. Climate Change and Psychological Well-being

The mental-health consequences of climate change can be understood through three interconnected pathways: direct exposure, indirect exposure, and anticipated threat. Direct exposure to disasters can produce acute fear and distress and may be followed by grief, trauma-related symptoms, sleep disturbance, anxiety, depression, and disruption of social functioning. Indirect exposure can occur through livelihood insecurity, displacement, food and water insecurity, repeated climate-related news, and perceptions of inadequate institutional response. Anticipatory threat involves worry about future health, employment, family, community, and quality of life.

Evidence increasingly supports an association between climate anxiety and psychological well-being. Gago *et al.* (2024), in a meta-analysis of 25 studies and 60 effect sizes, reported a moderate negative association between climate anxiety and psychological well-being ($r = -.296$, 95% CI $[-.360, -.230]$, $p < .001$). The relationship was stronger in samples with higher environmental identity and when well-being was assessed through indicators of psychological unwellness. Cosh *et al.* (2024) similarly reviewed evidence linking eco-anxiety with psychological distress and symptoms of major affective disorders, while noting variation in concepts and methods.

These findings should not be interpreted as evidence that environmental concern itself is pathological. Ojala *et al.* (2021) emphasize that worry and grief can be normal responses to genuine environmental threats and may support engagement. The distinction between adaptive concern and impairing distress is therefore essential for psychological assessment and intervention.

Table 1: Climate concern across a psychological continuum

Level	Psychological Experience	Possible Outcome
Environmental awareness	Knowledge and concern	Awareness and preparedness
Constructive concern	Worry with perceived efficacy	Sustainable action
Climate distress	Persistent emotional discomfort	Reduced well-being
Rumination/helplessness	Repetitive thoughts; low control	Avoidance and impairment

4. Coping, Hope and Psychological Resilience

Coping is a major mechanism through which climate-related concern influences psychological outcomes. Ojala (2012) identified problem-focused coping, meaning-focused coping, and de-emphasizing the seriousness of climate change among young people. Problem-focused and meaning-focused coping were associated with environmental engagement, whereas minimizing the threat was less constructive. Meaning-focused coping is particularly relevant because climate change is too complex to be solved by one individual. People may therefore benefit from

identifying meaningful actions within their sphere of influence while accepting limits to personal control.

Constructive coping may involve realistic problem solving, meaning-making, emotion regulation, social support, collective participation, balanced information use, and constructive hope. Hope in this context does not mean denying environmental risk. Rather, it involves recognizing risk while maintaining the belief that individual and collective actions can influence outcomes. Ojala's work suggests that hope connected with meaningful environmental engagement can support adaptive responses (Ojala, 2012).

Psychological resilience similarly does not mean emotional toughness or absence of distress. It involves the capacity to regulate difficult emotions, maintain functioning, seek support, solve problems, and adapt to changing circumstances. In climate-related contexts, resilience can include emotional, cognitive, behavioural, social, meaning-based, and collective dimensions. A resilient response therefore allows concern to coexist with agency and purposeful action.

5. Young People and the Indian Context

Young people are particularly important in climate psychology because they face prolonged exposure to climate uncertainty while having limited control over many political, economic, and institutional decisions. Hickman *et al.* (2021), in a global survey of 10,000 young people aged 16–25 years across ten countries including India, reported substantial climate-related worry and examined how emotional responses were associated with perceptions of government responses. Young people may experience uncertainty about their future, concern for family and future generations, frustration with institutional responses, and repeated exposure to climate-related information. At the same time, they should not be viewed only as vulnerable recipients of climate impacts; they can also be active participants in mitigation, adaptation, and environmental action (Hurley *et al.*, 2022).

Table 2: Selected climate-related psychological vulnerabilities in India

Population/Context	Climate-Related Stressor	Psychological Concern
Children and adolescents	Future uncertainty; disruption	Anxiety and fear
Farmers	Drought; rainfall variability; crop loss	Stress and financial distress
Coastal communities	Cyclones; flooding; displacement	Trauma, grief and anxiety
Urban populations	Heat; pollution; water insecurity	Stress and reduced well-being
Disaster-affected communities	Loss of home and livelihood	Grief, depression and trauma

India presents a particularly important setting because climate vulnerability intersects with socioeconomic inequality, livelihood dependence, urbanization, population density, and regional

differences. Agriculture and fisheries may be affected by changing weather patterns, while urban populations can face heat, pollution, water insecurity, and environmental degradation. Rural and coastal communities may experience livelihood disruption and displacement. Recent Indian reviews identify anxiety, depression, post-traumatic stress, stress, and other psychological vulnerabilities associated with climate-related hazards and emphasize the need for climate-sensitive mental-health responses (Mangalamchery & Uvais, 2025; Basistha *et al.*, 2025).

6. Psychological and Community-Based Responses

Psychological responses should recognize the legitimacy of environmental concern while preventing severe distress and functional impairment. Psychoeducation can help individuals distinguish adaptive concern from clinically significant anxiety and understand that emotions such as fear, sadness, anger, and grief may be understandable reactions to environmental threats. Cognitive-behavioural approaches can help identify catastrophic interpretations, excessive responsibility, and perceptions of absolute helplessness. The goal is balanced appraisal rather than unrealistic optimism.

Emotion-regulation strategies, including mindfulness, grounding, relaxation, emotional awareness, and acceptance-based approaches, may help individuals tolerate uncertainty. Meaning-focused approaches can connect environmental concerns with values, identity, and purpose. Peer-support and group interventions can reduce isolation and create opportunities for shared problem solving. When climate-related distress is persistent and associated with severe rumination, sleep disturbance, trauma symptoms, depression, or impairment in academic, occupational, or social functioning, professional mental-health assessment may be appropriate.

Climate change is also a collective psychological challenge. Social support can provide emotional reassurance, practical assistance, information, and a sense of belonging, while community participation can strengthen perceived efficacy. WHO (2022) recommends integrating climate considerations into mental-health programmes, integrating mental-health and psychosocial support into climate action, and using multisectoral and community-based approaches. Educational institutions can contribute through climate-health education, resilience programmes, peer support, sustainability activities, disaster preparedness, and accessible counselling. Such programmes should combine knowledge, emotional processing, agency, coping, and opportunities for meaningful action.

For India, climate-health planning should connect environmental sustainability, physical health, mental health, social protection, and community resilience. Psychological resilience should not be treated solely as an individual's responsibility; institutions and governments also have responsibilities to reduce environmental risks, strengthen social protection, improve mental-health services, and create opportunities for collective participation.

7. Research Gaps and Future Perspectives

Climate-psychology research is growing, but important gaps remain. Much evidence is cross-sectional, limiting causal interpretation and understanding of changes in climate anxiety over time. More longitudinal studies are needed, particularly following repeated exposure to climate-related hazards. Cultural and regional differences also require greater attention because emotional responses may vary with socioeconomic conditions, geography, occupation, community structure, and cultural meaning. The Indian evidence base requires more population-specific work involving students, farmers, coastal communities, disaster-affected populations, urban residents, and other vulnerable groups.

Intervention research is another priority. Compared with observational and conceptual work, fewer rigorous studies have evaluated psychological or community interventions using validated outcomes. Greater consistency in measuring climate anxiety, eco-anxiety, climate distress, ecological grief, and environmental worry would improve comparison across studies. Future research should also examine protective factors such as social support, self-efficacy, hope, meaning, emotional regulation, collective efficacy, and community participation. An interdisciplinary approach linking psychology, public health, environmental science, education, sociology, and climate policy is likely to be most useful.

Conclusion

Climate change is increasingly a psychological as well as an environmental and public-health challenge. Climate anxiety, eco-anxiety, ecological grief, and solastalgia provide useful concepts for understanding emotional responses to environmental change, but these responses should not automatically be interpreted as mental disorders. Concern, sadness, anger, and anxiety may be understandable reactions to genuine threats and can, under supportive conditions, contribute to awareness and action.

The central psychological challenge is to prevent legitimate concern from developing into debilitating helplessness. Psychological resilience can support this transition through emotional regulation, constructive hope, meaning-focused coping, perceived efficacy, social connectedness, environmental engagement, and community participation. Young people deserve particular attention because they face long-term uncertainty while having limited control over many environmental decisions. In India, climate vulnerability is further shaped by socioeconomic inequality, livelihood dependence, disaster exposure, and unequal access to mental-health services. A sustainable future therefore requires integration of environmental sustainability, physical health, mental health, and social resilience. Psychology can contribute not only by addressing distress, but also by strengthening the emotional, cognitive, social, and behavioural resources needed for constructive adaptation and collective action.

References

1. Albrecht, G., Sartore, G.-M., Connor, L., Higginbotham, N., Freeman, S., Kelly, B., Stain, H., Tonna, A., & Pollard, G. (2007). Solastalgia: The distress caused by environmental change. *Australasian Psychiatry*, 15(Suppl. 1), S95–S98. <https://doi.org/10.1080/10398560701701288>
2. Basistha, B., Paul, F. A., Bhuyan, K., Prasad, J. S. R., & Ali, A. (2025). Climate change and mental health in India: A narrative review of vulnerabilities, impacts, and resilience pathways. *Frontiers in Public Health*, 13, Article 1686876. <https://doi.org/10.3389/fpubh.2025.1686876>
3. Boehme, B. A. E., Kinsman, L. M., Norrie, H. J., Tessier, E. D., Fleming, S. W., & Asmundson, G. J. G. (2024). Climate anxiety: Current evidence and future directions. *Current Psychiatry Reports*, 26(11), 670–677. <https://doi.org/10.1007/s11920-024-01538-9>
4. Clayton, S., & Karazsia, B. T. (2020). Development and validation of a measure of climate change anxiety. *Journal of Environmental Psychology*, 69, Article 101434. <https://doi.org/10.1016/j.jenvp.2020.101434>
5. Cosh, S. M., Ryan, R., Fallander, K., Robinson, K., Tognela, J., Tully, P. J., & Lykins, A. D. (2024). The relationship between climate change and mental health: A systematic review of the association between eco-anxiety, psychological distress, and symptoms of major affective disorders. *BMC Psychiatry*, 24, Article 833. <https://doi.org/10.1186/s12888-024-06274-1>
6. Gago, T., Sargisson, R. J., & Milfont, T. L. (2024). A meta-analysis on the relationship between climate anxiety and wellbeing. *Journal of Environmental Psychology*, 94, Article 102230. <https://doi.org/10.1016/j.jenvp.2024.102230>
7. Hickman, C., Marks, E., Pihkala, P., Clayton, S., Lewandowski, R. E., Mayall, E. E., Wray, B., Mellor, C., & van Susteren, L. (2021). Climate anxiety in children and young people and their beliefs about government responses to climate change: A global survey. *The Lancet Planetary Health*, 5(12), e863–e873. [https://doi.org/10.1016/S2542-5196\(21\)00278-3](https://doi.org/10.1016/S2542-5196(21)00278-3)
8. Hogg, T. L., Stanley, S. K., O'Brien, L. V., Wilson, M. S., & Watsford, C. R. (2021). The Hogg Eco-Anxiety Scale: Development and validation of a multidimensional scale. *Global Environmental Change*, 71, Article 102391. <https://doi.org/10.1016/j.gloenvcha.2021.102391>
9. Hurley, E. A., Dalglish, S. L., & Sacks, E. (2022). Supporting young people with climate anxiety: Mitigation, adaptation, and resilience. *The Lancet Planetary Health*, 6(3), Article e190. [https://doi.org/10.1016/S2542-5196\(22\)00015-8](https://doi.org/10.1016/S2542-5196(22)00015-8)

10. Mangalamchery, V., & Uvais, N. A. (2025). Climate change and mental health: A scoping review of Indian studies. *Primary Care Companion for CNS Disorders*, 27(4), Article 24r03903.
11. Ojala, M. (2012a). How do children cope with global climate change? Coping strategies, engagement, and well-being. *Journal of Environmental Psychology*, 32(3), 225–233. <https://doi.org/10.1016/j.jenvp.2012.02.004>
12. Ojala, M. (2012b). Hope and climate change: The importance of hope for environmental engagement among young people. *Environmental Education Research*, 18(5), 625–642. <https://doi.org/10.1080/13504622.2011.637157>
13. Ojala, M., Cunsolo, A., Ogunbode, C. A., & Middleton, J. (2021). Anxiety, worry, and grief in a time of environmental and climate crisis: A narrative review. *Annual Review of Environment and Resources*, 46, 35–58. <https://doi.org/10.1146/annurev-environ-012220-022716>
14. World Health Organization. (2022). *Mental health and climate change: Policy brief*. <https://www.who.int/publications/i/item/9789240045125>

Nutraceuticals: Concepts, Classification, Health Benefits And Emerging Applications for Human Health In A Changing Environment

Palla Sravani Sreeja*, V. Sony, T. Gayatri, N. Nivya and Dipali Kumar Singh

Department of Home Science,
St. Joseph's College for Women (A), India

*Corresponding author E-mail: sreejapalla2000@gmail.com

Abstract

Globally, the burden of non-communicable illnesses is rising due to increased pollution, sedentary lifestyles, changed eating habits, and strain on food systems brought on by climate change. There is increasing interest in foods and food-derived chemicals that can promote normal physiological function and assist prevent disease in addition to traditional treatment. Nutraceuticals are situated at the nexus of pharmacology and nutrition. This chapter provides a comprehensive overview of the area, starting with the notion and background of nutraceuticals and its connection to dietary supplements and functional foods. The main bioactive components- polyphenols, carotenoids, omega-3 fatty acids, dietary fiber, and bioactive peptides- as well as their modes of action are then reviewed, along with a classification based on chemical nature and source. Anaemia, gut health, diabetes, obesity, cancer, bone and cognitive health, and cardiovascular health are all taken into consideration. With an emphasis on the Indian context, the chapter also covers advancements in delivery and encapsulating technologies, the bioavailability challenge, and market-influencing safety, quality control, and regulatory issues.

Keywords: Gut Microbiota, Bioavailability, Bioactive Compounds, Nutraceuticals, Non-Communicable Diseases and Functional Foods.

1. Introduction

Food has long been prized for purposes other than its caloric value. Some foods and spices have been traditionally recognized in Ayurveda, Unani and traditional Chinese medicine to maintain health and correct imbalances for a long time. Commonly used examples in Indian households are fermented dairy, amla, ginger and fenugreek or turmeric. Currently, at the cellular level, modern nutrition research is beginning to answer the question of why many of these behaviors were effective. In 1989, Stephen De Felice, founder of the Foundation for Research in Medicine, coined the term “Nutraceutical”, which is derived from the word’s “nutrition” and “pharmaceutical”. It refers to a food or a part of the food which has an additional health benefit other than mere sustenance, like prevention and cure of a disease (Kalra, 2003). One of the earliest official attempts to recognize the physiological benefits of foods was the Health

Ministry's "Foods for Specified Health Use" (FOSHU) approval system, which was created after Japanese scientists discovered "functional foods" in the 1980s (Shimizu, 2003).

It is important to distinguish between nutraceuticals and related categories since they are frequently confused to be the same. A conventional food is eaten primarily for its nutrition, taste and fullness. A functional food is a food that has been processed, or naturally contains, ingredients that confer a health benefit, such as probiotic yoghurt, or fortified cereals. A nutraceutical is typically a purified or concentrated bioactive or a product made from a bioactive and is often marketed in dosages like capsules, tablets, powders or extracts. Dietary supplements are similar to nutraceuticals, but are primarily intended to provide vitamins, minerals and amino acids to the diet. In fact, the differences are not distinct and similar substances, like curcumin, are eaten as a spice, as a food fortification, or as a concentrated supplement. (Kalra, 2003)

2. Classification and Major Sources of Nutraceuticals

2.1 Classification

Table 1: Major classes of nutraceuticals with representative examples

Major Classes	Examples	Sources
Nutrient based	Minerals, vitamins, vital fatty acids, and amino acids	Legumes, fruits, veggies, and fish oil
Phytochemicals	Flavonoids, carotenoids, polyphenols, and phytosterols	Green tea, soy, tomatoes and turmeric
Prebiotics and probiotics	Lactobacillus and Bifidobacterium strains; inulin and oligosaccharides	Curd, fermented foods, onion, banana, and chicory
Enzymes and bioactive peptides	Papain, bromelain, milk-derived peptides	Legume proteins, dairy, papaya, and pineapple
Herbal nutraceuticals	Ashwagandha, amla, fenugreek, tulsi	Medicinal plants, botanical extracts, spices
Dietary fiber	Psyllium, pectin, and β -glucan	Fruit peels, seed husks, and oats

Source: Compiled by the author(s) from Chanda et al. (2019) and Das et al. (2012).

There are a number of ways to classify nutraceuticals with no single classification scheme that is accepted globally. A common means is to make a distinction between the degree of alteration of the source. Traditional nutraceuticals are natural, usually minimally processed food sources that provide an identified bio-active, e.g., tomatoes as a source of lycopene and oily fish as a source of omega-3 fatty acids. Non-traditional nutraceuticals refer to those nutraceuticals that have been specifically altered or developed such as fortified foods, biotechnology-derived ingredient and enriched formulations (Chanda *et al.*, 2019). Another method of classification is on the basis of their chemical properties and their functions. According to Das *et al.* (2012) food products used

as nutraceuticals fall under the following categories: dietary fibre, prebiotics, probiotics, polyunsaturated fatty acids, antioxidants, and herbal or natural foods. These views are summarized in the classes of this chapter (Table 1).

Nutrient based nutraceuticals are vitamins, minerals, amino acids and fatty acids with benefits other than their role in preventing deficiencies. Non-nutrient types (principally the phytochemicals) are not required for life and are found to affect physiological processes. Microbiological groups are very precisely defined. Probiotics are defined as a live microorganism that confers a health benefit to the host when administered in adequate amounts (Hill *et al.*, 2014) and prebiotics as a substrate that can be selectively used by host microorganisms to confer a health benefit (Gibson *et al.*, 2017). Bioactive peptides are small protein fragments with a length of 2 to 20 amino acids, which are not active in the parent protein but are released during digestion, fermentation or enzymatic hydrolysis (Korhonen & Pihlanto, 2006).

2.2 Major Sources

Plants continue to be the greatest source. Fruits, vegetables, cereals, legumes, nuts, spices and medicinal herbs are rich in polyphenols, carotenoids, fibre and phytosterols; much of the interest in turmeric, green tea and soy is due to their high content of bio actives. The contribution of animals and marine sources is not the same. Milk proteins are well studied bioactive peptide sources, and the primary dietary source of long-chain omega 3 fatty acids are fish and algal oils. Examples of microbial sources are probiotic bacteria and yeasts and microorganisms used in fermentation to produce vitamins, organic acids and peptides.

Traditional fermented foods are the links between several of these groups. Live microbes and fermentation products are provided in a normal meal as a curd, idli and dosa batter, kanji and fermented rice (chaddannam) in households of coastal Andhra. Food proteins can also be broken down to bioactive peptides during the fermentation process (Korhonen & Pihlanto, 2006) which further makes the food a source of new bio actives, as well as a probiotic carrier.

3.Key Bioactive components and mechanisms of action.

3.1 Major Bioactive Components

- **Polyphenols and Flavonoids:** Polyphenols are secondary plant metabolites and flavonoids are one of the most important sub-classes. In epidemiological studies, consumption of polyphenol rich diets has been linked with a reduced risk of cancer, cardiovascular disease, diabetes, osteoporosis and neurodegenerative disease (Pandey & Rizvi, 2009). The one well-known to everyone is curcumin, which is found in turmeric. It is believed to have antioxidant and anti-inflammatory properties and its bioavailability is not as high due to its poor absorption, quick metabolism and elimination, however use of black pepper (piperine) enhances its bioavailability (Hewlings & Kalman, 2017).

- **Carotenoids:** Carotenoids are the pigments behind the colours of many fruits and vegetables. Others, e.g., β -carotene, provide vitamin A, and lycopene, which lacks provitamin A activity, is a powerful antioxidant and singlet oxygen quencher (Rao & Rao, 2007).
- **Phytosterols:** Plant sterols and plant stanols lower the amount of cholesterol absorbed in the intestine. They reduce LDL-cholesterol by about 8-10% per day and this effect is in addition to the effect of statins (Gylling *et al.*, 2014).
- **Omega-3 Fatty Acids:** The long-chain fatty acids EPA and DHA from fish and algal oils are incorporated into cell membranes and alter their composition. This affects the way in which cells communicate with each other and the type of lipid mediators they produce and increases the concentration of non-inflammatory eicosanoids generated from EPA instead of arachidonic acid. (Calder, 2010).
- **Dietary Fibre:** Fiber is associated with reduced cardiovascular disease and decreases body weight. Fermentable fibres and oligosaccharides like inulin arrive in the colon where the gut flora of your body ferments it, stimulating *Bifidobacterium* (Slavin, 2013).
- **Bioactive Peptides:** Milk and other food proteins can yield peptides with antioxidant, antihypertensive, antithrombotic, antimicrobial and immunomodulatory properties (Korhonen & Pihlanto, 2006).
- **Vitamins and Minerals:** They function as enzyme cofactors and as antioxidants (vitamins C and E, selenium, zinc), and are important in bone health (calcium and vitamin D), oxygen transport (iron).

Table 2: Selected bioactive components, sources and principal actions

Bioactive	Example Dietary Source	Principal Action	Reference
Polyphenols (e.g., curcumin)	Turmeric, tea, fruits	Antioxidant, anti-inflammatory	Hewlings & Kalman (2017); Pandey & Rizvi (2009)
Carotenoids (e.g., lycopene)	Tomato, carrot, papaya	Singlet oxygen quenching; provitamin A (some)	Rao & Rao (2007)
Phytosterols	Vegetable oils, nuts, seeds	Reduced cholesterol absorption	Gylling <i>et al.</i> (2014)
Omega-3 (EPA, DHA)	Oily fish, algal oil	Altered membrane composition and eicosanoid profile	Calder (2010)
Dietary fibre and prebiotics	Oats, legumes, chicory	Colonic fermentation; <i>Bifidobacterium</i> stimulation	Slavin (2013)
Bioactive peptides	Milk, legume proteins	Antihypertensive, antioxidant, immunomodulatory	Korhonen & Pihlanto (2006)

Source: Compiled by the author(s) from the studies cited.

3.2 Mechanisms of Action

The mechanisms of action are very similar and occur through a few overlapping pathways. The most notable is the antioxidant activity. Oxidative stress is related to numerous chronic diseases and polyphenols and carotenoids limit the oxidative stress by neutralising reactive species (Pandey & Rizvi, 2009; Rao & Rao, 2007). The anti-inflammatory effects come from a number of pathways such as the anti-inflammatory signaling effect of curcumin and the alteration of the eicosanoid profile caused by omega-3 fatty acids (Calder, 2010; Hewlings & Kalman, 2017). Fibre, prebiotics and certain polyphenols are associated to health through modulation of gut microbiota. Fibre feeds support healthy bacteria and produce short-chain fatty acids (Slavin, 2013).

In observational data, a single compound typically works through multiple of these pathways, suggesting that whole food and multi-component nutraceuticals might offer more health benefits than isolated compounds because of the synergistic interactions among bioactive compounds in the whole food.

4. Health Benefits and Disease Management

4.1 Cardiovascular Health

Control of cholesterol has the strongest level of support. At an average intake of roughly 2 g/day, plant sterols and stanols decrease LDL-cholesterol by 8-10%, and boost the effect of statins (Gylling *et al.*, 2014). Omega-3 supplementation was associated with a reduced risk of cardiovascular mortality and non-fatal myocardial infarction (MI) in a meta-analysis (Khan *et al.*, 2021). Thus, the benefit will depend on the dose or formulation. Additionally, higher fibres consumption is associated with lower cardiovascular diseases (Slavin, 2013).

4.2 Diabetes, Obesity and Metabolic Syndrome

The most popular study of curcumin is its effect on glycaemic control. No type 2 diabetes occurred in any of the 240 adults with prediabetes in Thailand who took curcumin in a nine-month, randomised trial compared with 16.4% of placebo takers, and insulin sensitivity and β -cell function were improved. This is one trial in one population and needs to be replicated in Indian groups. Other reviews have shown that curcumin can benefit metabolic syndrome (Hewlings & Kalman, 2017) and increased fibre consumption is associated with decreased body weight (Slavin, 2013). These results indicate a role in obesity or diabetes prevention, but not as a replacement for diet, activity or medication.

4.3 Cancer

Epidemiological studies have linked diets high in plant foods with reduced cancer risk, but individual supplements have not consistently been shown to provide these benefits. In the Finnish ATBC trial of 29,133 smokers, β -carotene supplementation (20 mg/day) led to a 18% increased risk of lung cancer and vitamin E supplementation had no effect on lung cancer incidence (Alpha-Tocopherol, Beta Carotene Cancer Prevention Study Group [ATBC], 1994). It is important to remember that the benefits found with whole foods cannot be taken for granted in regards to concentrated single compounds, particularly in high-risk groups.

4.4 Bone, Cognitive Health and Healthy Ageing

A meta-analysis of 8 randomised trials (30,970 adults) found calcium + vitamin D reduced total fractures by approximately 15% and there was a less consistent and smaller effect on hip fracture (Weaver *et al.*, 2016). In population studies, polyphenol-rich diets have been shown to reduce the risk of neurodegenerative disease (Pandey & Rizvi, 2009), but there is a dearth of evidence from controlled trials regarding the effect of polyphenol supplements on cognitive health.

4.5 Anemia, Micronutrient Deficiencies, and Thyroid Health

Micronutrient deficiencies are a major problem in India. In NFHS-5 (2019–21), anemia affected 57.0% of women aged 15–49 and 67.1% of children aged 6–59 months (International Institute for Population Sciences [IIPS] & ICF, 2021). Iron, folate, and vitamin B12-rich meals and fortified products make sense because women are particularly burdened. Both iodine and selenium are necessary for the thyroid to mediate antioxidant defense and thyroid hormone metabolism. A review associates selenium supplementation to autoimmune thyroiditis with a decrease in anti-thyroid peroxidase antibody levels (Ventura *et al.*, 2017).

4.6 Postbiotics and the Gut–Brain/Gut–Immune Axes

The concept of gut health has been expanded beyond the use of probiotics and prebiotics, and now includes postbiotics – bioactive substances generated as a result of microbial fermentation. These can consist of short-chain fatty acids, enzymes, cell wall fragments, and signaling molecules, which can also have physiological effects without the presence of living microorganisms. (Tsilingiri & Rescigno, 2013). The gut–brain axis refers to the two-way traffic between the gut and the brain via neural, endocrine and immunologic pathways. Short-chain fatty acids are one type of microbial metabolites that can affect the production of neurotransmitters, stress responses and mood regulation. Likewise, the gut–immune axis connects the activity of the gut flora to immune responses in the whole body, and a healthy intestinal flora promotes immune tolerance and lowers chronic low-grade inflammation. These effects are mediated in part by the ability of dietary fibre, polyphenols and fermented food to influence the composition and metabolism of the gut microbiota.

5. Nutraceuticals and Gut Health

For many nutraceuticals, the gut is the initial target and several have an impact on other organs. There are four associated types of microbe products, which are now formally defined and summarised in Table 3.

Postbiotics are not living organisms and can be suitable for products where it is challenging to maintain the viability of the microbes. The combination of the two categories is based on the simple premise that prebiotic fibres sustain the resident microbiota, whose fermentation products promote gut health (Slavin, 2013).

In the immune system, commensal microbes train immune responses, protect against infection and maintain balance of inflammation, disruption of commensal relationships are associated with chronic inflammatory disease. The effects of nutraceuticals that can also modify the microbiota may consequently be quite different from digestion effects, but most of these connections are

only associations, and a clinical benefit must be demonstrated for each nutraceutical product and strain.

Table 3: Biotic categories relevant to gut health

Category	Working Definition	Typical Example
Probiotic	Live microorganisms that give a health benefit to the host when given in adequate amounts (Hill <i>et al.</i> , 2014)	<i>Lactobacillus</i> in curd
Prebiotic	A substrate selectively used by host microorganisms to give a health benefit (Gibson <i>et al.</i> , 2017)	Inulin, oligosaccharides
Synbiotic	A mixture of live microorganisms and substrate(s) selectively used by host microorganisms that together give a health benefit (Swanson <i>et al.</i> , 2020)	<i>Bifidobacterium</i> with FOS
Postbiotic	A preparation of inactivated microorganisms and/or their components that gives a health benefit (Salminen <i>et al.</i> , 2021)	Heat-killed bacterial cells

Source: Compiled by the author(s) from the ISAPP consensus statements cited.

6. Functional Foods and Emerging Technologies and Bioavailability

6.1 Functional foods, fortification and biofortification.

The benefit is not isolated but part of the meal in functional foods, which contain nutraceutical bioactives that can be achieved as a component of the food eaten on a regular basis (Kalra, 2003). The development of one requires selection of a bioactive that has demonstrated benefit, stability during processing and storage, acceptable taste and texture of the final product, and evidence of benefit in the final product. Micronutrients are added to widely consumed staple foods through fortification. The minimum and maximum levels of fortification of wheat flour, rice, salt, milk and edible oil have been prescribed by the Food Safety and Standards (Fortification of Foods) Regulations, 2018, to provide approximately 30-50% of the daily requirements (FSSAI, 2018).

6.2 Emerging Technologies

Much of the bioactives are hydrophobic, light and air sensitive and poorly absorbed, which means that delivery technology plays a major role in whether or not a nutraceutical will work. The compound is protected by the encapsulation and it can even enhance its release. For instance, non-polar bioactives, like vitamins A, D and E, β -carotene, lycopene and curcumin, have been encapsulated, protected and delivered with the help of nanoemulsion technology. In the same manner, in the case of using a powdered, stable ingredient, it can be microencapsulated, for example, by spray drying; and in the case of controlled release, the intention is to release the bioactive in the right place and at the right time. Other routes are provided by biotechnology and fermentation, as bioactive peptides may be obtained from food proteins by microbial fermentation and enzymatic hydrolysis (Korhonen & Pihlanto, 2006). However, new extraction methods are emerging such as ultrasound-assisted extraction, microwave-assisted

extraction and supercritical fluid-assisted extraction for purer bioactives and less solvent. Before the wide use of nanomaterials in foods, they require continued assessment of safety.

6.3 Bioavailability and Bioaccessibility

For example, a food may be very rich in one compound but lack in the other because the body is unable to use it for health benefits. Bioavailability entails release from the food, absorption, distribution, metabolising and elimination, and is influenced by the bioaccessibility, food matrix, transporters, molecular structure and metabolising enzymes. Curcumin is poorly absorbed, quickly metabolised and eliminated, and is enhanced by piperine (Hewlings & Kalman, 2017).

7. Safety, quality control and regulation.

7.1 Safety and Drug–Nutrient Interactions

Not all natural is safe at any dosage. More lung cancer was observed in those who took high dose β -carotene (ATBC, 1994) and there was an association with more bleeding with omega-3 fatty acids alone (Khan *et al.*, 2021). Not all natural is safe even at low doses. The following two were provided in Section 4. High levels of β -carotene were associated with a higher risk of lung cancer in smokers (ATBC, 1994); and omega-3 fatty acids alone were associated with an increased risk of bleeding and atrial fibrillation (Khan *et al.*, 2021).

7.2 Quality Control and Standardisation

Safe and Effective Products begin with Real Raw Material. A chemical authentication study was carried out for 2,386 commercial herbal products from 37 countries in 2021, in which 27% of the products were found to be adulterated (Ichim & Booker, 2021). Standardisation is also to be introduced for potency as a function of shelf life. In India, the declared overages (if any) are a way for manufacturers to cover losses that may occur during the storage process, and a “minus 10%” tolerance zone is permitted for the analysis, as per FSSAI (2021). The products should also meet the National limits of heavy metals and other contaminants (FSSAI 2021).

8. Future Perspectives

The future of nutrition might be defined by personalised nutrition. Even though the same food was served during the same meal to the same person in 800 studies, the blood glucose response was vastly different and a machine-learning model that included blood parameters, diet, body measurements, physical activity and gut microbiota was able to predict the response reasonably well. A randomised dietary intervention, based on the model, then reduced post-meal glucose (Zeevi *et al.*, 2015). Taking the same approach to nutraceuticals, product selection, dose and combination one day may be matched to an individual's microbiome and metabolism, though, as with the precision nutrition idea, this concept requires a new round of trials.

The by-products of the food industry are rich sources of fibres, polyphenols and proteins which can be recovered and utilized as food chain additives, supplements or fortificants. If quality, safety and standardisation are maintained as with other sources they could help to reduce waste and reduce pressure on primary crops.

Conclusion

Nutraceuticals are in between food and medicine, and they depend on more than just the existence of a bioactive compound. In some cases, there is convincing evidence of benefit (e.g., plant sterols for cholesterol), and in some less convincing or conflicting evidence (e.g., high dose antioxidants, omega-3 supplements). Bioavailability, dose and product quality and interactions with medicines determine whether a product will help or harm. Some improvements in the field are necessary to enhance the functionality, such as the delivery technology, gut focused products and regulation, which includes a developing Indian regulatory framework; however, labelling and claims supported by trials remain a key requirement. Well selected and well-regulated nutraceuticals can contribute to the prevention, in addition to a balanced diet and healthcare, but not in place of them in a period of increasing lifestyle diseases and environmental stress.

References

1. Alpha-Tocopherol, Beta Carotene Cancer Prevention Study Group. (1994). The effect of vitamin E and beta carotene on the incidence of lung cancer and other cancers in male smokers. *New England Journal of Medicine*, 330(15), 1029–1035. <https://doi.org/10.1056/NEJM199404143301501>
2. Calder, P. C. (2010). Omega-3 fatty acids and inflammatory processes. *Nutrients*, 2(3), 355–374. <https://doi.org/10.3390/nu2030355>
3. Chanda, S., Tiwari, R. K., Kumar, A., & Singh, K. (2019). Nutraceuticals inspiring the current therapy for lifestyle diseases. *Advances in Pharmacological Sciences*, 2019, Article 6908716, 1–5. <https://doi.org/10.1155/2019/6908716>
4. Das, L., Bhaumik, E., Raychaudhuri, U., & Chakraborty, R. (2012). Role of nutraceuticals in human health. *Journal of Food Science and Technology*, 49(2), 173–183. <https://doi.org/10.1007/s13197-011-0269-4>
5. Food Safety and Standards Authority of India. (2018). *Food Safety and Standards (Fortification of Foods) Regulations, 2018*. Government of India. <https://www.fssai.gov.in>
6. Food Safety and Standards Authority of India. (2021). *Frequently asked questions (FAQs) on the Food Safety and Standards (Health Supplements, Nutraceuticals, Food for Special Dietary Use, Food for Special Medical Purpose, Functional Food and Novel Food) Regulations*, 2016. https://www.fssai.gov.in/upload/uploadfiles/files/FAQs_Nutraceutical_Regulations_06_10_2020.pdf
7. Food Safety and Standards Authority of India. (2022). *Direction under Section 16(5) of the Food Safety and Standards Act, 2006: Operationalisation of FSS (Health Supplements, Nutraceuticals, Food for Special Dietary Use, Food for Special Medical Purpose and Prebiotic and Probiotic Food) Regulations*, 2022.

https://www.fssai.gov.in/upload/advisories/2022/03/6243ef28079ceDirection_Nutra_30_03_2022.pdf

8. Gibson, G. R., Hutkins, R., Sanders, M. E., Prescott, S. L., Reimer, R. A., Salminen, S. J., Scott, K., Stanton, C., Swanson, K. S., Cani, P. D., Verbeke, K., & Reid, G. (2017). Expert consensus document: The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of prebiotics. *Nature Reviews Gastroenterology & Hepatology*, 14(8), 491–502. <https://doi.org/10.1038/nrgastro.2017.75>
9. Gylling, H., Plat, J., Turley, S., Ginsberg, H. N., Ellegård, L., Jessup, W., Jones, P. J., Lütjohann, D., Maerz, W., Masana, L., Silbernagel, G., Staels, B., Borén, J., Catapano, A. L., De Backer, G., Deanfield, J., Descamps, O. S., Kovanen, P. T., Riccardi, G., ... Chapman, M. J. (2014). Plant sterols and plant stanols in the management of dyslipidaemia and prevention of cardiovascular disease. *Atherosclerosis*, 232(2), 346–360. <https://doi.org/10.1016/j.atherosclerosis.2013.11.043>
10. Hewlings, S. J., & Kalman, D. S. (2017). Curcumin: A review of its effects on human health. *Foods*, 6(10), Article 92. <https://doi.org/10.3390/foods6100092>
11. Hill, C., Guarner, F., Reid, G., Gibson, G. R., Merenstein, D. J., Pot, B., Morelli, L., Canani, R. B., Flint, H. J., Salminen, S., Calder, P. C., & Sanders, M. E. (2014). Expert consensus document: The International Scientific Association for Probiotics and Prebiotics consensus statement on the scope and appropriate use of the term probiotic. *Nature Reviews Gastroenterology & Hepatology*, 11(8), 506–514. <https://doi.org/10.1038/nrgastro.2014.66>
12. Ichim, M. C., & Booker, A. (2021). Chemical authentication of botanical ingredients: A review of commercial herbal products. *Frontiers in Pharmacology*, 12, Article 666850. <https://doi.org/10.3389/fphar.2021.666850>
13. International Institute for Population Sciences, & ICF. (2021). *National Family Health Survey (NFHS-5), 2019–21: India*. International Institute for Population Sciences.
14. Kalra, E. K. (2003). Nutraceutical: Definition and introduction. *AAPS PharmSci*, 5(3), Article 25. <https://doi.org/10.1208/ps050325>
15. Khan, S. U., Lone, A. N., Khan, M. S., Virani, S. S., Blumenthal, R. S., Nasir, K., Miller, M., Michos, E. D., Ballantyne, C. M., Boden, W. E., & Bhatt, D. L. (2021). Effect of omega-3 fatty acids on cardiovascular outcomes: A systematic review and meta-analysis. *EClinicalMedicine*, 38, Article 100997. <https://doi.org/10.1016/j.eclinm.2021.100997>
16. Korhonen, H., & Pihlanto, A. (2006). Bioactive peptides: Production and functionality. *International Dairy Journal*, 16(9), 945–960. <https://doi.org/10.1016/j.idairyj.2005.10.012>
17. Pandey, K. B., & Rizvi, S. I. (2009). Plant polyphenols as dietary antioxidants in human health and disease. *Oxidative Medicine and Cellular Longevity*, 2(5), 270–278. <https://doi.org/10.4161/oxim.2.5.9498>

18. Rao, A. V., & Rao, L. G. (2007). Carotenoids and human health. *Pharmacological Research*, 55(3), 207–216. <https://doi.org/10.1016/j.phrs.2007.01.012>
19. Salminen, S., Collado, M. C., Endo, A., Hill, C., Lebeer, S., Quigley, E. M. M., Sanders, M. E., Shamir, R., Swann, J. R., Szajewska, H., & Vinderola, G. (2021). The International Scientific Association of Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of postbiotics. *Nature Reviews Gastroenterology & Hepatology*, 18(9), 649–667. <https://doi.org/10.1038/s41575-021-00440-6>
20. Shimizu, T. (2003). Health claims on functional foods: The Japanese regulations and an international comparison. *Nutrition Research Reviews*, 16(2), 242–244. <https://doi.org/10.1079/NRR200363>
21. Slavin, J. (2013). Fiber and prebiotics: Mechanisms and health benefits. *Nutrients*, 5(4), 1417–1435. <https://doi.org/10.3390/nu5041417>
22. Swanson, K. S., Gibson, G. R., Hutkins, R., Reimer, R. A., Reid, G., Verbeke, K., Scott, K. P., Holscher, H. D., Azad, M. B., Delzenne, N. M., & Sanders, M. E. (2020). The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of synbiotics. *Nature Reviews Gastroenterology & Hepatology*, 17(11), 687–701. <https://doi.org/10.1038/s41575-020-0344-2>
23. Tsilingiri, K., & Rescigno, M. (2013). Postbiotics: What else? *Gut Microbes*, 4(6), 1–4. <https://doi.org/10.4161/gmic.25884>
24. Ventura, M., Melo, M., & Carrilho, F. (2017). Selenium and thyroid disease: From pathophysiology to treatment. *International Journal of Endocrinology*, 2017, Article 1297658. <https://doi.org/10.1155/2017/1297658>
25. Weaver, C. M., Alexander, D. D., Boushey, C. J., Dawson-Hughes, B., Lappe, J. M., LeBoff, M. S., Liu, S., Looker, A. C., Wallace, T. C., & Wang, D. D. (2016). Calcium plus vitamin D supplementation and risk of fractures: An updated meta-analysis from the National Osteoporosis Foundation. *Osteoporosis International*, 27(1), 367–376. <https://doi.org/10.1007/s00198-015-3386-5>
26. Zeevi, D., Korem, T., Zmora, N., Israeli, D., Rothschild, D., Weinberger, A., Ben-Yacov, O., Lador, D., Avnit-Sagi, T., Lotan-Pompan, M., Suez, J., Mahdi, J. A., Matot, E., Malka, G., Kosower, N., Rein, M., Zilberman-Schapira, G., Dohnalová, L., Pevsner-Fischer, M., ... Segal, E. (2015). Personalized nutrition by prediction of glycemic responses. *Cell*, 163(5), 1079–1094. <https://doi.org/10.1016/j.cell.2015.11.001>

INNOVATIONS IN FOOD AND NUTRITION FOR SUSTAINABLE LIVING: A BIOLOGICAL SCIENCE PERSPECTIVE

Radhika Bandaroo

Govt. Sarvodya Kanya Vidyalaya, Mohan Garden, New Delhi 10059

Corresponding author E-mail: radhikabandaroo@gmail.com

Abstract

The growing global population, climate change, environmental degradation, loss of biodiversity, water scarcity, food waste, and the increasing prevalence of nutrition-related disorders have created an urgent need for sustainable food systems. Innovations in food and nutrition provide important opportunities to address these challenges while improving human health and protecting ecological resources. From a Biological Science perspective, sustainable food systems involve the application of principles of plant biology, microbiology, biotechnology, genetics, ecology, nutrition science, and food technology. This paper examines major innovations including bio-fortification, plant-based proteins, millets and indigenous crops, probiotics and fermented foods, alternative proteins, precision agriculture, hydroponics, vertical farming, food fortification, functional foods, biotechnology, sustainable food preservation, and biological methods of food-waste management. The study is based on a descriptive and analytical review of secondary information obtained from scientific literature, international organizations, and authoritative publications. The analysis indicates that nutritional quality and environmental sustainability should be considered together rather than as separate objectives. Diverse diets rich in vegetables, fruits, pulses, whole grains, nuts and other nutrient-dense foods can support human health while potentially reducing environmental pressures. WHO recognizes that healthy diets can also be environmentally sustainable when they emphasize diversity and appropriate consumption of plant-based foods. Bio-fortification provides another biological pathway for improving micronutrient density in staple crops through plant breeding, agronomic practices, and biotechnology. Similarly, reducing food loss and waste is essential because food loss and waste contribute to greenhouse-gas emissions, resource depletion, and biodiversity pressures. The study concludes that combining modern biological innovations with traditional knowledge, local food systems, responsible consumption, and effective policy can create healthier, more resilient, resource-efficient, and sustainable food systems for present and future generations.

Keywords: Sustainable Food Systems, Food Innovation, Nutrition, Biotechnology, Biofortification, Probiotics, Functional Foods, Millets, Food Waste, Biological Science, Sustainable Living, Food Security.

Introduction

Food is one of the fundamental requirements for human survival, health and development. However, the contemporary food system faces multiple interconnected challenges. Population

growth, urbanization, climate change, soil degradation, water scarcity, declining biodiversity, changing dietary patterns and food waste are placing increasing pressure on agricultural and natural resources. At the same time, malnutrition exists in multiple forms. Undernutrition and micronutrient deficiencies coexist with overweight, obesity and diet-related non-communicable diseases. A healthy diet requires adequate energy, protein, vitamins and minerals from a diversity of foods. WHO emphasizes the importance of vegetables, fruits, whole grains, legumes, nuts and other nutrient-dense foods while limiting excessive amounts of unhealthy fats, free sugars and salt. The concept of sustainable living requires individuals and communities to meet present needs without compromising the ability of future generations to meet their own needs. Food is central to this concept because its production, processing, transportation, consumption and disposal are closely connected with land, water, energy, biodiversity and climate. The relationship between food and sustainability is therefore multidimensional. A sustainable food system should provide sufficient, safe, nutritious and affordable food while minimizing environmental damage. WHO describes healthy and sustainably produced diets as having potential benefits for both human and planetary health. Biological Science provides a strong foundation for developing such systems. Plant breeding, genetics, microbiology, biotechnology, ecology and nutritional biology can be applied to improve crop productivity, nutritional quality, resistance to environmental stress and resource efficiency. Innovations such as biofortification, probiotics, fermentation, alternative proteins, precision agriculture, hydroponics, vertical farming, functional foods and biological waste management represent important pathways towards sustainable food production and consumption. Food loss and waste are also major sustainability concerns. FAO reports that food loss and waste have significant consequences for food security, nutrition, environmental pollution, ecosystems and biodiversity and contribute an estimated 8–10% of global greenhouse-gas emissions. Therefore, the present study explores food and nutrition innovations through a biological science perspective and examines their contribution to sustainable living.

Objectives of the Study

The major objectives of the study are:

- To examine the relationship between food, nutrition and sustainable living from a Biological Science perspective.
- To identify major innovations in food production, processing and nutrition that contribute to sustainability.
- To examine the role of biotechnology and bio-fortification in improving nutritional security.
- To analyse the contribution of alternative proteins, functional foods, probiotics and traditional foods to sustainable nutrition.
- To examine biological approaches for reducing food loss and waste.

- To identify the role of sustainable agricultural practices and indigenous crops in conserving natural resources and biodiversity.
- To suggest strategies for promoting sustainable food and nutrition practices among individuals, educational institutions, communities and policymakers.

Literature Review

3.1 Healthy and Sustainable Diets: WHO emphasizes that a healthy diet should be diverse and nutrient-dense, with appropriate quantities of fruits, vegetables, legumes, whole grains, nuts and other nutritious foods. Evidence also indicates that healthy dietary patterns can have environmental advantages. The concept of sustainable diets extends the idea of nutrition beyond individual health to include environmental, economic and social dimensions. Sustainable dietary approaches seek to balance nutritional adequacy with resource conservation and environmental protection. Fanzo has discussed the relationship between healthy and sustainable diets and the achievement of Sustainable Development Goal, emphasizing the importance of transforming food systems to simultaneously address food security, nutrition and sustainability.

3.2 Biofortification: Biofortification is an important biological innovation in nutrition. WHO defines it as improving the nutritional quality of food crops through agronomic practices, conventional breeding or modern biotechnology. Examples include iron-biofortified beans and pearl millet, zinc-biofortified wheat and rice, and provitamin-A-rich crops. Biofortification is particularly relevant in populations where micronutrient deficiencies are prevalent and access to supplements or commercially fortified foods may be limited.

3.3 Food Fortification: Food fortification involves deliberately adding essential vitamins and minerals to foods. WHO identifies fortification as an evidence-informed intervention for reducing micronutrient deficiencies, including iron and iodine deficiency. Fortification can complement dietary diversification, supplementation and other nutrition interventions. However, it should be implemented based on population needs, consumption patterns, safety considerations and appropriate monitoring.

3.4 Probiotics and Fermented Foods: The human digestive system contains a complex community of microorganisms collectively known as the gut microbiota. Fermented foods containing beneficial microorganisms and probiotic products have received increasing scientific attention because of their potential relationship with digestive health and overall well-being. Traditional fermentation of foods such as curd, yoghurt, idli, dosa and other fermented products demonstrate how indigenous biological knowledge can contribute to food preservation and nutritional quality.

3.5 Alternative Proteins: Increasing demand for protein has encouraged research into plant-based proteins, algae, microbial proteins and cultivated meat. Pulses, legumes, soy, peas, cereals and millets can contribute substantially to plant-based protein intake. Alternative protein systems may reduce dependence on resource-intensive livestock production, although their

nutritional quality, affordability, processing requirements and environmental performance must be evaluated carefully.

3.6 Sustainable Agriculture: Sustainable agriculture emphasizes efficient use of soil, water and biological resources. Organic farming, integrated pest management, agroforestry, crop rotation, conservation agriculture and precision farming are examples of approaches that can reduce environmental pressures. Hydroponics, aeroponics and vertical farming are additional innovations that can enable food production in locations where land availability is limited.

3.7 Food Loss and Waste: Food waste represents both a nutritional and environmental problem. FAO reports that food loss occurs substantially along the supply chain, while additional food waste occurs at retail, food-service and household levels. Biological approaches such as composting, anaerobic digestion, fermentation and conversion of agricultural residues into useful products can contribute to a circular bioeconomy.

Research Methodology

The present study adopts a descriptive, analytical and review-based research methodology.

4.1 Nature of the Study: The study is conceptual and exploratory in nature. It examines innovations in food and nutrition through principles of Biological Science and their relevance to sustainable living.

4.2 Sources of Data: The study is based primarily on secondary data collected from:

- World Health Organization publications
- Food and Agriculture Organization reports
- Peer-reviewed research literature
- Books and academic publications
- Scientific reports on food, nutrition and biotechnology
- Publications relating to sustainable agriculture and food systems □ Relevant institutional and government reports

4.3 Method of Analysis: The collected information was organized under major themes:

- Sustainable food production
- Nutritional innovation
- Biotechnology and biofortification
- Alternative proteins
- Functional and fermented foods
- Indigenous crops
- Food preservation
- Food loss and waste management
- Biodiversity conservation
- Sustainable consumption

A qualitative descriptive analysis was undertaken to determine how these innovations contribute to nutritional security, resource conservation, environmental sustainability and human health.

4.4 Scope of the Study: The study focuses particularly on the biological dimensions of food innovation rather than technological or economic aspects alone. It emphasizes the connection between biological resources, nutrition, human health and ecological sustainability.

Major Innovations in Food and Nutrition

5.1 Biofortification: Biofortification combines agricultural science and nutrition. Crops can be developed with enhanced concentrations of essential nutrients such as:

- Iron
- Zinc
- Vitamin A precursors
- Protein
- Essential amino acids

It can be achieved through conventional plant breeding, agronomic interventions and biotechnology.

5.2 Biotechnology in Food Production: Biotechnology can help develop:

- Disease-resistant crops
- Drought-tolerant crops
- Nutrient-rich varieties
- Improved fermentation systems
- Enzyme-based food processing
- Microbial protein
- Improved food preservation methods

Gene-editing technologies represent an emerging area of research for improving selected agricultural traits.

5.3 Millets and Indigenous Crops: Millets are particularly relevant to sustainable nutrition because they can be incorporated into diverse diets and are suited to several semi-arid agricultural environments. Examples include:

- Pearl millet
- Finger millet
- Foxtail millet
- Little millet
- Kodo millet
- Barnyard millet

They can contribute carbohydrates, protein, minerals, dietary fibre and other bioactive components.

5.4 Probiotics and Fermented Foods: Fermentation is one of the oldest biological food technologies. Microorganisms can transform raw food materials and influence taste, texture, preservation and nutritional characteristics. Probiotic and fermented foods can therefore connect traditional food practices with modern nutritional science.

5.5 Functional Foods: Functional foods contain biologically active components that may provide benefits beyond basic nutrition. Examples include foods containing:

- Dietary fibre
- Probiotics
- Prebiotics
- Antioxidants
- Omega-3 fatty acids
- Polyphenols
- Plant sterols

However, health claims should be supported by appropriate scientific evidence.

5.6 Alternative Protein Sources: Alternative proteins include:

- Pulses and legumes
- Soy-based foods
- Pea protein
- Algae
- Microbial proteins
- Insect protein in appropriate cultural contexts
- Cultivated animal-cell products

The biological and nutritional advantages of each alternative must be evaluated in terms of amino-acid quality, digestibility, micronutrient content, processing and environmental impact.

5.7 Hydroponics and Vertical Farming: Hydroponic systems grow plants without conventional soil, while vertical farming uses vertically arranged growing systems. Potential advantages include:

- Efficient water use
- Reduced land requirement
- Controlled growing conditions
- Local production
- Year-round cultivation

However, energy requirements and economic feasibility need to be considered when assessing their overall sustainability.

Major Findings of the Study

The objectives of the study are fulfilled through the following findings:

Objective	Major Findings
Objective 1	Food, nutrition, human health and environmental sustainability are closely interconnected.
Objective 2	Biofortification, probiotics, alternative proteins, vertical farming and functional foods are important innovations.
Objective 3	Biotechnology and biofortification can improve the nutrient density of staple crops.
Objective 4	Plant proteins, fermented foods, probiotics, millets and functional foods can contribute to sustainable nutrition.
Objective 5	Composting, fermentation and anaerobic digestion can reduce the environmental impact of food waste.
Objective 6	Sustainable agriculture and indigenous crops can contribute to resource conservation and biodiversity.
Objective 7	Nutrition education, sustainable food policies, community participation and institutional initiatives can accelerate adoption.

Suggestions and Recommendations

7.1 Promote Biofortified Crops: Government agencies and agricultural institutions should promote scientifically validated biofortified varieties of crops such as rice, wheat, maize, pulses and millets where nutritional deficiencies justify their use.

7.2 Encourage Millet-Based Diets: Millets should be incorporated into school, college and community nutrition programmes wherever locally appropriate. Their nutritional properties and role in diversified diets should be communicated through nutrition education.

7.3 Strengthen Nutrition Education: Educational institutions should introduce practical programmes on:

- Balanced diets
- Food labels
- Food safety
- Sustainable consumption
- Food waste reduction
- Local and seasonal foods
- Kitchen gardening

7.4 Promote Sustainable Agriculture: Farmers should be encouraged to adopt:

- Crop rotation
- Integrated pest management
- Soil conservation
- Water-efficient irrigation

- Agroforestry
- Organic and biological inputs where appropriate
- Precision agriculture

7.5 Reduce Food Waste: Households, hotels, educational institutions and food businesses should introduce food-waste monitoring and segregation systems. Unused organic food and agricultural residues should be directed towards appropriate composting, animal feed or anaerobic digestion systems, subject to safety requirements.

7.6 Support Research in Alternative Proteins: Research institutions should investigate affordable, nutritious and culturally acceptable alternative protein sources while evaluating their environmental impacts and food safety.

7.7 Promote Traditional Biological Knowledge: Traditional fermentation, food preservation, indigenous crops and local food systems should be scientifically documented and evaluated.

7.8 Encourage Sustainable Food Packaging: Research and industry should explore biodegradable and compostable food-packaging materials while ensuring food safety, shelf life and affordability.

7.9 Establish Sustainable Food Laboratories in Educational Institutions: Colleges and universities can establish small laboratories or demonstration units for:

- Food analysis
- Fermentation
- Composting
- Kitchen gardens
- Hydroponics
- Nutrition education
- Food-waste management

This would provide students with experiential learning.

7.10 Adopt a One Health Perspective: Food sustainability should be considered through a One Health framework, recognizing the interconnectedness of human health, animal health and ecosystem health.

Conclusion

Innovations in food and nutrition have the potential to transform the way societies produce, process, consume and manage food. From a Biological Science perspective, sustainability is not simply a technological challenge; it is an interdisciplinary challenge involving organisms, ecosystems, nutrition, human health and natural resources. Biofortification can improve the nutritional value of staple crops, while biotechnology can contribute to climate resilience and improved agricultural productivity. Probiotics, fermentation and functional foods demonstrate the importance of microorganisms and biological processes in nutrition. Plant-based and alternative proteins can diversify protein sources, while millets and indigenous crops can

strengthen local food systems. Hydroponics, vertical farming and precision agriculture provide new approaches to efficient food production. At the same time, food waste must be treated as a major sustainability concern. FAO emphasizes that reducing food loss and waste is essential for food security, nutrition and environmental protection. The most effective pathway is therefore not dependence on a single innovation but the integration of biological science, traditional knowledge, sustainable agriculture, nutrition education, responsible consumption and supportive public policy. A sustainable food future should achieve three interconnected outcomes: healthy people, resilient food systems and a healthy planet. The successful integration of scientific innovation with local knowledge and community participation can make sustainable living a practical reality for present and future generations.

References

1. Food and Agriculture Organization of the United Nations. (2024). *Food loss and food waste*. FAO Policy Support and Governance Gateway.
2. Fanzo, J. (2019). Healthy and sustainable diets and food systems: The key to achieving Sustainable Development Goal 2. *Food Ethics*, 4, 159–174.
3. World Health Organization. (2018). *A healthy diet sustainably produced: Information sheet*. World Health Organization.
4. World Health Organization. (2026). *Healthy diet*. World Health Organization.
5. World Health Organization. (2023). *Biofortification of staple crops*. WHO eLENA.
6. World Health Organization. (2017). Talsma, E. F., & Pachón, H. *Biofortification of crops with minerals and vitamins*. WHO eLENA.
7. World Health Organization. (2022). *Food fortification: Questions and answers*. World Health Organization.
8. World Health Organization. (2006). *Guidelines on food fortification with micronutrients*. World Health Organization.
9. World Health Organization. (2018). *Healthy diet: Fact sheet No. 394*. World Health Organization.
10. World Health Organization. (2026). *Micronutrients*. World Health Organization.

FROM CROP TO HUMAN HEALTH: ASSESSING THE NUTRITIONAL IMPACT OF BIOFORTIFICATION IN INDIA

P. Sindhu Priya*, K. Jagannadham, P. Deepa and B. Sagarika

Department of Clinical Nutrition Dietetics and Food Science,

School of Allied and Healthcare Sciences,

Malla Reddy University, Hyderabad, Telangana, India

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

Abstract

Micronutrient deficiencies remain an important nutritional concern in India, particularly among vulnerable population groups. Biofortification offers a food-based approach in which the nutrient content of crops is increased through plant breeding, agronomic practices or other biological methods. This chapter reviews the nutritional potential of biofortified crops in India, with emphasis on iron, zinc and provitamin A. Evidence from Indian studies on pearl millet and wheat is considered along with the factors that determine whether increased nutrient concentration results in meaningful nutritional benefits. The chapter discusses bioavailability, absorption, dietary intake, meal composition and food-processing effects because these factors influence the amount of a nutrient ultimately available to the body. Human intervention studies indicate that iron-biofortified pearl millet can improve indicators of iron status, while zinc-biofortified wheat can increase dietary zinc intake without necessarily producing a measurable improvement in plasma zinc. The potential benefits of provitamin A-biofortified crops similarly depend on carotenoid retention, bio accessibility, absorption and conversion to vitamin A. Overall, biofortification has potential to strengthen micronutrient intake through commonly consumed staple foods and can complement dietary diversification, supplementation and conventional food fortification.

Keywords: Biofortification, Micronutrient Deficiencies, Bioavailability, Nutritional Status, India.

Introduction

Micronutrients are vitamins and minerals required in small amounts, but they are essential for growth, development, metabolism and overall health. Micronutrient deficiencies continue to be an important public-health concern in India, affecting different population groups to varying degrees. A systematic review and meta-analysis have highlighted the continuing burden of micronutrient deficiencies among the Indian population [1].

Poor micronutrient intake can result from inadequate dietary diversity, changing food habits, economic and agricultural changes, lifestyle factors, increased nutritional requirements during

pregnancy and lactation, infections and other health conditions [2]. Deficiencies may contribute to anaemia, impaired growth and development, reduced cognitive performance, increased susceptibility to illness and lower productivity.

The consequences of malnutrition extend beyond individual health. Undernourished children may experience impaired physical and cognitive development, while micronutrient deficiencies in adults can affect health and work capacity. Such effects may continue across generations and contribute to persistent cycles of poor health and poverty [3,4]. Dietary diversification, supplementation and conventional food fortification are established approaches for addressing micronutrient deficiencies. Biofortification provides another food-based strategy in which the nutritional quality of crops is improved during crop development through plant breeding, agronomic practices or other biological methods. Since biofortified crops can be incorporated into commonly consumed staple foods, they may improve nutrient intake through regular diets without requiring major changes in food habits [5-7].

Biofortification: Concept and Approaches

Biofortification refers to increasing the nutritional value of food crops through agricultural and biological methods. Unlike conventional food fortification, where nutrients are added during food processing or preparation, biofortification aims to increase the nutrient content of the crop itself before it reaches the consumer [5,6].

Conventional plant breeding uses naturally occurring genetic variation to identify and develop varieties with higher concentrations of specific nutrients. Agronomic biofortification involves the application of nutrients such as zinc or selenium through fertilizers or other crop-management practices. Modern biotechnology and genetic approaches can also be used to modify pathways involved in nutrient accumulation. Conventional breeding remains important because it can be incorporated into existing agricultural systems and can produce nutrient-dense varieties of staple crops. Examples include iron-biofortified pearl millet, zinc-biofortified wheat and provitamin A-rich crops. The most suitable approach depends on the crop, target nutrient, growing conditions and nutritional needs of the population [6,7].

Biofortification is therefore being explored as a potentially sustainable way of improving micronutrient intake, particularly among populations that depend heavily on staple crops and may have limited access to diverse diets or other nutrition interventions [5-7].

Biofortification of Major Micronutrients in India

Iron Biofortification

Iron deficiency remains an important micronutrient concern in India. Iron-biofortified pearl millet has consequently received considerable attention as a food-based approach for improving iron intake and nutritional status. Pearl millet is an important cereal in several parts of India and can serve as a useful vehicle for increasing dietary iron intake. Through breeding approaches,

pearl millet varieties with higher iron concentrations than conventional varieties have been developed. Importantly, human intervention studies indicate that this increase in crop iron can translate into improvements in indicators of iron status. Children who were iron deficient at baseline were also more likely to become iron-replete after consuming the biofortified pearl millet [8].

Zinc Biofortification

Zinc biofortification has been studied particularly in staple cereals such as wheat and rice. Increasing the zinc concentration of commonly consumed crops provides an opportunity to improve dietary zinc intake without requiring major changes in usual food practices. Agronomic biofortification of wheat through foliar zinc application has been investigated among Indian children. In a randomized controlled trial, zinc-biofortified wheat contained substantially more zinc than conventional wheat and increased dietary zinc intake when included in school meals. However, the intervention did not result in a significant improvement in plasma zinc concentration or zinc deficiency [9].

Provitamin A Biofortification

Provitamin A biofortification aims to increase carotenoids in crops that can be converted by the body into vitamin A. Crops investigated for this purpose include maize, sweet potato, cassava and rice. The nutritional value of these crops depends on carotenoid concentration, retention during processing, bio accessibility, absorption and conversion to active vitamin A [10,11].

In India, crop biofortification has been recognized as an important component of strategies for improving nutritional security, with research focusing on crop varieties capable of providing higher amounts of essential micronutrients through foods already present in the regular diet [10].

From Biofortified Crop to Human Health

Bioavailability and Absorption

A higher nutrient concentration in a crop does not automatically mean that the same increase will be available to the human body. The nutrient must first be released from the food matrix, become bio accessible and then be absorbed and utilized. For minerals such as iron and zinc, bioavailability can be influenced by antinutritional factors, particularly phytate, as well as interactions among nutrients and the individual's nutritional and physiological status. For provitamin A carotenoids, the food matrix and presence of dietary fat can influence bioavailability [11,12].

Recent evidence suggests that biofortified crops can provide improved bioaccessibility and bioavailability of target micronutrients compared with conventional crops, although the extent of the benefit varies with the crop, nutrient and processing conditions [12].

Dietary Intake and Meal Context

Regular consumption is essential if biofortified crops are to provide meaningful nutritional benefits. The amount consumed, frequency of intake and overall composition of the meal influence how much of the target nutrient is ultimately available to the body. Meal composition is particularly relevant for provitamin A carotenoids, as dietary fat can enhance carotenoid absorption. For iron and zinc, phytate and other components of the diet can influence absorption. Therefore, the nutritional contribution of a biofortified food needs to be considered as part of the complete meal and overall dietary pattern rather than in isolation [11,12].

Effect of Food Processing

Food processing can influence the nutritional value of biofortified crops in both positive and negative ways. Processes such as soaking, germination, fermentation and cooking may reduce certain antinutritional compounds and improve mineral bioavailability. On the other hand, some processing conditions can result in losses of heat-sensitive or oxidation-sensitive nutrients. For provitamin A-rich crops, processing may disrupt the food matrix and improve carotenoid release and bio accessibility. However, excessive heating or prolonged processing may reduce carotenoid retention. Similarly, appropriate processing can reduce phytate and improve mineral availability [11,12].

Evidence from Human Studies and Nutritional Outcomes

Dietary Consumption of Biofortified Crops

The nutritional impact of biofortified crops ultimately depends on how well they are incorporated into the usual diet. Crops such as pearl millet, wheat, rice and maize are widely consumed in India, making them useful vehicles for delivering additional micronutrients through regular meals. One advantage of biofortification is that people can obtain additional nutrients through foods that are already familiar and commonly consumed. However, the potential benefit still depends on the amount and frequency of consumption, adherence to the intervention and the nutritional composition of the overall diet [5,13].

Evidence from Human Intervention Studies

Human intervention studies are particularly important because they help determine whether an increase in the nutrient content of a crop actually translates into measurable nutritional benefits. The randomized trial of iron-biofortified pearl millet among schoolchildren in Maharashtra provides important evidence from India. After six months of consumption, children who received iron-biofortified pearl millet showed improvements in serum ferritin and total body iron compared with those consuming conventional pearl millet. The effect was particularly evident among children who were iron deficient at baseline [8]

Evidence for zinc biofortification is somewhat different. In an Indian school-based randomized controlled trial, agronomically biofortified wheat increased dietary zinc intake compared with

conventional wheat. However, there was no significant improvement in plasma zinc concentration or zinc deficiency. This suggests that an increase in nutrient intake does not always lead to an observable change in nutritional biomarkers over a relatively short intervention period [9].

Another randomized trial among Indian school-going adolescents examined functional outcomes following consumption of iron-biofortified pearl millet. The study reported improvements in attention and memory, suggesting that potential effects of biofortification may extend beyond biochemical measures of nutrient status [14].

Nutritional Outcomes

Overall, available human evidence indicates that biofortification can increase intake of target micronutrients and, under suitable conditions, improve selected indicators of nutritional status. Among the Indian studies considered here, evidence is particularly encouraging for iron-biofortified pearl millet, where improvements in iron status have been demonstrated in schoolchildren [8].

For zinc, biofortification can increase the amount of zinc supplied through the diet, but the physiological response may depend on absorption, phytate content, overall dietary composition and baseline zinc status [9,11].

For provitamin A-biofortified crops, nutritional outcomes depend on carotenoid concentration, retention during processing, bioaccessibility, absorption and conversion to vitamin A. Therefore, the nutritional benefit cannot be predicted from the nutrient concentration of the crop alone [10-12].

Applications, Challenges and Future Perspectives

Biofortification has practical relevance because staple crops can deliver additional nutrients through familiar foods and existing food systems. Its application can support nutrition programmes aimed at populations that rely heavily on cereals and have limited access to diverse diets. However, successful implementation depends on the availability and acceptance of biofortified varieties, regular consumption and the local dietary context. A major challenge is that increased nutrient concentration does not always result in a proportional improvement in human nutritional status. Antinutritional factors, dietary inhibitors, food processing, nutrient interactions, absorption and baseline nutritional status can influence the final outcome. Evaluation should therefore extend beyond crop nutrient content to include bioavailability and human health outcomes [11,12].

Conclusion

Biofortification has considerable potential to improve micronutrient intake and contribute to nutritional security in India through nutrient-enhanced staple crops such as pearl millet, wheat, rice and maize. Evidence from human studies, particularly those involving iron-biofortified pearl

millet, indicates that biofortified crops can improve selected indicators of micronutrient status. At the same time, the nutritional impact depends not only on nutrient concentration but also on regular consumption, bioavailability, absorption, antinutritional factors and food-processing practices. Biofortification should therefore be viewed as a complementary food-based strategy rather than a replacement for existing nutrition interventions. When combined with dietary diversification, supplementation and conventional food fortification, it may contribute to a broader approach for addressing micronutrient deficiencies. Continued research on bioavailability, processing, dietary consumption and long-term health outcomes will help clarify its role in improving nutritional health in India.

References

1. Bechoff, A., & Dhuique-Mayer, C. (2017). Factors influencing micronutrient bioavailability in biofortified crops. *Annals of the New York Academy of Sciences*, 1390(1), 74–87.
2. Development Initiatives. (2017). *Global nutrition report 2017: Nourishing the SDGs*. Development Initiatives.
3. Finkelstein, J. L., Mehta, S., Udipi, S. A., Ghugre, P. S., Luna, S. V., Wenger, M. J., *et al.* (2015). A randomized trial of iron-biofortified pearl millet in school children in India. *The Journal of Nutrition*, 145(7), 1576–1581. <https://doi.org/10.3945/jn.114.208009>
4. Finkelstein, J. L., Mehta, S., Udipi, S. A., Ghugre, P. S., Luna, S. V., Wenger, M. J., *et al.* (2018). Cognitive performance in Indian school-going adolescents is positively affected by consumption of iron-biofortified pearl millet: A 6-month randomized controlled efficacy trial. *The Journal of Nutrition*, 148(12), 2012–2020.
5. Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., *et al.* (2018). Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. *Frontiers in Nutrition*, 5, Article 12.
6. Huey, S. L., Mehta, N. H., Konieczynski, E. M., Bhargava, A., Friesen, V. M., Krisher, J. T., *et al.* (2024). Bioaccessibility and bioavailability of biofortified food and food products: Current evidence. *Critical Reviews in Food Science and Nutrition*, 64(14), 4500–4522.
7. Indian Council of Medical Research, & National Institute of Nutrition. (2020). *Nutrient requirements for Indians: Recommended dietary allowances and estimated average requirements: Report of the expert group, 2020*. ICMR-NIN.
8. Langyan, S., Yadava, P., Khan, F. N., Bhardwaj, R., Tripathi, K., Bhardwaj, V., *et al.* (2022). Nutritional and food composition survey of major pulses toward healthy, sustainable, and biofortified diets. *Frontiers in Sustainable Food Systems*, 6, 87269.

9. Naik, B., Kumar, V., Rizwanuddin, S., Mishra, S., Kumar, V., Saris, P. E. J., *et al.* (2024). Biofortification as a solution for addressing nutrient deficiencies and malnutrition. *Heliyon*, 10(9), Article e30595.
10. Signorell, C., Kurpad, A. V., Pauline, M., Shenvi, S., Mukhopadhyay, A., King, J. C., *et al.* (2023). The effect of zinc biofortified wheat produced via foliar application on zinc status: A randomized, controlled trial in Indian children. *The Journal of Nutrition*, 153(10), 3092–3100.
11. UNICEF, World Health Organization, & World Bank Group. (2018). *Levels and trends in child malnutrition: Key findings of the 2018 edition of the Joint Child Malnutrition Estimates*. UNICEF, World Health Organization, & World Bank Group.
12. Venkatesh, U., Sharma, A., Ananthan, V. A., Subbiah, P., Durga, R., & CSIR Summer Research Training Team. (2021). Micronutrient deficiency in India: A systematic review and meta-analysis. *Journal of Nutritional Science*, 10, Article e110.
13. Wakeel, A., & Labuschagne, M. T. (2021). Editorial: Crop biofortification for food security in developing countries. *Frontiers in Sustainable Food Systems*, 5, Article 756296.
14. Yadava, D. K., Hossain, F., & Mohapatra, T. (2018). Nutritional security through crop biofortification in India: Status and future prospects. *The Indian Journal of Medical Research*, 148(5), 621–631.

INTEGRATED NUTRIENT MANAGEMENT IN SUSTAINABLE AGRICULTURE

Landa Urmila

Department of Agriculture and Rural Development,
St. Joseph's College for Women (A), Visakhapatnam

Abstract

Integrated Nutrient Management (INM) is an important approach for achieving sustainable agricultural production through the balanced and efficient use of nutrients from organic, inorganic, and biological sources. It aims to maintain soil fertility, improve nutrient-use efficiency, sustain crop productivity, and reduce adverse environmental impacts. Continuous nutrient removal through crop production, nutrient imbalance, declining soil organic matter, and inefficient fertilizer use can affect soil health and long-term agricultural productivity. INM addresses these concerns by integrating farmyard manure, compost, green manures, crop residues, biofertilizers, mineral fertilizers, soil amendments, and appropriate nutrient-management technologies. Recent developments in INM encompass a wide range of approaches such as microbial inoculants, vermin-composting, bio-char, slow- and controlled-release fertilizers, nano fertilizers, sensors, drones, GIS, and digital decision-support systems. Site-specific nutrient management and soil testing further improve the efficiency of nutrient application. However, adoption is constrained by inadequate awareness, limited availability of quality organic and biological inputs, variability in soil and climate, and institutional and policy-related limitations. Integrating INM with climate-smart agriculture, precision nutrient management, improved extension services, and efficient input supply chains can contribute to resilient and sustainable agricultural systems.

Keywords: Integrated Nutrient Management, Sustainable Agriculture, Soil Fertility, Nutrient-Use Efficiency, Organic Manures, Biofertilizers, Soil Health, Climate-Smart Agriculture.

1. Introduction

Agricultural production depends fundamentally on the availability of essential plant nutrients. Nitrogen (N), phosphorus (P), and potassium (K) are the primary nutrients, while secondary nutrients and micronutrients are also required for normal plant growth and development. Soil productivity depends not only on nutrient availability but also on physical, chemical, and biological properties such as organic matter, structure, acidity, water-holding capacity, and microbial activity. Thus, sustainable nutrient management must consider the soil as a living resource rather than simply a medium for supplying fertilizers.

Modern agriculture has substantially increased food production through improved varieties, irrigation, fertilizers, crop protection, and improved management practices. However, continuous cultivation without adequate nutrient replacement can progressively deplete soil nutrient reserves. Conversely, excessive or poorly balanced nutrient application can cause economic losses and environmental problems. Nutrients need to be supplied in appropriate quantities, proportions, forms, and at suitable times.

Integrated Nutrient Management (INM) has emerged as a systematic approach to these challenges. It involves the planned and balanced use of available nutrient sources, including organic manures, crop residues, green manures, biofertilizers, and mineral fertilizers. The objective is to optimize nutrient supply from different sources according to crop requirements and soil conditions. INM is therefore closely associated with maintaining soil fertility while sustaining agricultural productivity (Gruhn *et al.*, 2000; Yadav *et al.*, 2025).

2. Concept and Objectives of INM

Integrated Nutrient Management may be defined as the planned and judicious integration of organic, inorganic, and biological sources of plant nutrients to maintain soil fertility, improve nutrient-use efficiency, and sustain crop productivity while minimizing environmental degradation. Mineral fertilizers provide nutrients in readily available forms, organic materials contribute organic matter and gradually release nutrients, and beneficial microorganisms can contribute to nutrient transformation, biological nitrogen fixation, and nutrient solubilization.

The major objectives of INM are to:

- Maintain and improve soil fertility and soil health;
- Provide balanced nutrition according to crop requirements;
- Improve nutrient-use efficiency and reduce nutrient losses;
- Integrate organic, inorganic, and biological nutrient sources;
- Recycle nutrients available within the farm;
- Improve soil physical, chemical, and biological properties;
- Reduce unnecessary dependence on external inputs;
- Improve economic efficiency and long-term productivity; and
- Minimize environmental degradation while supporting climate-resilient agriculture.

3. Principles of Integrated Nutrient Management

3.1 Balanced Use of Nutrients

Fertilizer application should be based on soil-test information, crop nutrient requirements, yield targets, and the nutrient-supplying capacity of the soil. Applying nutrients in appropriate proportions and quantities can reduce the risk of both inadequate and excessive fertilization, thereby promoting more efficient use of applied nutrients.

3.2 Integration of Nutrient Sources

INM combines farmyard manure, compost, green manure, crop residues, biofertilizers, mineral fertilizers, and suitable amendments. The combination is selected according to local availability, crop requirement, soil condition, cost, and expected response.

3.3 Site-Specific Nutrient Management

Nutrient requirements differ with soil type, crop, climate, variety, irrigation, previous crop, and management practices. Site-specific nutrient management therefore uses local soil and crop information to determine the appropriate source, rate, time, and method of nutrient application.

3.4 Synchronization of Supply and Crop Demand

Nutrient application should be synchronized with the crop's growth stages and nutrient demand. Using suitable application schedules, split applications, efficient placement methods, and advanced fertilizer formulations can enhance nutrient availability to plants while minimizing losses caused by leaching, surface runoff, and volatilization.

3.5 Recycling of Nutrients

Crop residues, animal manures, compost, green manures, and other organic materials can return nutrients and carbon to agricultural soils. Recycling strengthens nutrient cycling and reduces avoidable losses from the farm system.

4. Components of Integrated Nutrient Management

INM uses multiple nutrient sources rather than relying on a single input. The major components and their roles are summarized below.

Component	Examples	Major Role
Organic manures	FYM, compost, vermicompost	Add organic matter and nutrients; improve soil condition
Green manures	Dhaincha, sunnhemp, Sesbania	Add biomass and contribute biologically fixed nitrogen
Crop residues	Straw, stubble, legume residues	Recycle nutrients and carbon
Biofertilizers	Rhizobium, Azotobacter, Azospirillum, PSB	Biological N fixation and nutrient solubilization
Mineral fertilizers	Urea, DAP, SSP, MOP	Supply readily available plant nutrients
Soil amendments	Lime, gypsum	Correct specific soil constraints and improve nutrient availability
Precision tools	Sensors, GIS, UAVs	Support site-specific nutrient diagnosis and application

5. Organic Sources of Nutrients

5.1 Farmyard Manure and Compost

Farmyard manure (FYM), compost, and other well-stabilized organic amendments serve as important sources of nutrients and organic matter in agricultural soils. Their regular application can improve soil physical properties by promoting stable soil aggregation, increasing water-holding capacity, enhancing porosity and aeration, and reducing compaction. These amendments also contribute to improved chemical properties by increasing nutrient availability, cation exchange capacity, buffering capacity, and nutrient retention. In addition, the organic substrates support beneficial soil microorganisms, stimulate microbial activity, and promote nutrient cycling, thereby strengthening the biological functioning of the soil. Collectively, these improvements contribute to better soil structure, fertility, soil quality, and overall soil health. Properly managed composting also provides an environmentally sound approach for recycling agricultural residues and household organic wastes while reducing the accumulation of organic waste.

5.2 Green Manure and Crop Residues

Green manuring involves growing suitable plants and incorporating their biomass into the soil. Leguminous green manures are especially useful for biological nitrogen contribution. Crop residues also represent an important source of nutrients and carbon. Their appropriate retention or incorporation supports nutrient cycling and soil organic matter maintenance.

5.3 Vermicompost and Recycled Organic Materials

Vermi-composting is a biological process in which earthworms, together with associated microorganisms, decompose organic residues and transform them into a stabilized, nutrient-rich soil amendment. Other recycled materials, including properly treated agricultural and agro-industrial wastes, can also contribute to nutrient recycling. Such materials should be assessed for nutrient content and possible contaminants before field application.

6. Biofertilizers and Microbial Inputs

Biofertilizers are formulations containing beneficial microorganisms that support plant nutrition by enhancing nutrient availability, nutrient transformation, or the efficiency of nutrient uptake. Symbiotic bacteria such as *Rhizobium* facilitate biological nitrogen fixation in compatible leguminous crops, whereas free-living (*Azotobacter*) and associative (*Azospirillum*) bacteria can contribute to nitrogen availability and promote plant growth. Phosphate-solubilizing microorganisms enhance phosphorus availability by converting relatively insoluble forms into forms that can be more readily absorbed by plants. Similarly, arbuscular mycorrhizal fungi establish beneficial associations with plant roots and can improve the acquisition of nutrients and water, particularly under suitable soil and crop conditions.

The recent literature emphasizes increasing use of microbial inoculants and biological fertilizers as part of INM. Their effectiveness depends on the quality of the inoculant, compatibility with the crop and soil, environmental conditions, and correct application.

7. Role of Chemical Fertilizers in INM

INM does not imply complete elimination of mineral fertilizers. Chemical fertilizers remain important where soil nutrient supplies are insufficient to meet crop demand. Their role in INM is to supply required nutrients in appropriate quantities and proportions, at suitable growth stages and by methods that minimize losses. The objective is efficient and balanced fertilizer use rather than indiscriminate fertilizer application.

Soil-test-based recommendations, split application, appropriate placement, and improved formulations can increase fertilizer-use efficiency. The integration of mineral fertilizers with organic and biological sources can help maintain both immediate nutrient supply and longer-term soil quality (Gruhn *et al.*, 2000; Yadav *et al.*, 2025).

8. INM, Soil Health and Crop Productivity

Soil health is a major foundation of sustainable agriculture. INM contributes to soil health by combining nutrient supply with organic matter management and biological activity. Organic inputs can improve soil structure, water-holding capacity, aeration, microbial activity, nutrient retention, and nutrient cycling.

Adequate and balanced nutrient supply is also essential for crop yield and quality. Nutrient deficiency can restrict crop growth, whereas excessive application can reduce nutrient-use efficiency and increase losses. By combining nutrient sources with different release characteristics and synchronizing supply with crop demand, INM supports productive soils and more stable crop performance.

9. Nutrient-Use Efficiency and Environmental Benefits

Nutrient-use efficiency describes how effectively crops acquire and utilize supplied nutrients for biomass and economic yield. INM can improve nutrient-use efficiency through balanced fertilization, soil testing, appropriate timing and placement, organic matter management, biofertilizers, crop rotations, efficient irrigation, and precision nutrient management.

Poor nutrient management may contribute to nutrient losses, water contamination, soil degradation, and greenhouse-gas emissions. INM seeks to reduce these risks through balanced nutrient supply, recycling, and better synchronization of nutrient availability with plant demand. Healthy soils with adequate organic matter can also contribute to greater resilience under drought and other climatic stresses (Amanullah *et al.*, 2023).

10. Recent Advances in INM

10.1 Vermicomposting and Biochar

Vermicomposting is a biological process in which earthworms and microorganisms convert biodegradable organic residues into a stable, nutrient-rich amendment that can improve soil fertility and support organic waste recycling. Biochar is a carbon-rich, porous material produced through the thermal conversion of biomass under oxygen-limited conditions. Its application to soil can enhance nutrient retention, improve soil properties, contribute to carbon storage, and support long-term soil quality. Together, vermicomposting and biochar-based approaches provide valuable opportunities for organic waste recycling, soil conditioning, nutrient retention, and carbon management.

10.2 Microbial Consortia

Current research is increasingly focused on the combined application of beneficial microorganisms, with the aim of creating synergistic effects that enhance nutrient availability, stimulate root development and activity, and improve the plant's ability to acquire and utilize essential nutrients.

10.3 Slow- and Controlled-Release Fertilizers

These fertilizers are designed to release nutrients progressively and can help synchronize nutrient supply with crop demand while reducing potential losses.

10.4 Nanofertilizers

Nanofertilizers are nutrient formulations in which nutrients are delivered through nanoscale materials, carriers, or particles to improve their availability and utilization by crops. Their small particle size and high surface area can facilitate more efficient nutrient delivery and, in some formulations, allow nutrients to be released gradually in response to environmental or plant-related conditions. This is an emerging technology being investigated for improved nutrient delivery and nutrient-use efficiency. Their agronomic and environmental performance requires appropriate evaluation.

10.5 Precision and Digital Nutrient Management

Sensors, remote sensing, UAVs, GIS, soil mapping, and decision-support systems are increasingly being used to diagnose nutrient variability and support site-specific recommendations.

11. INM under Climate Change

Climate variability changes nutrient availability, crop demand, soil processes, and the risk of nutrient losses. INM can be integrated with conservation agriculture, efficient irrigation, crop diversification, residue management, integrated farming systems, and climate-resilient varieties. The 2023 literature links INM with improved soil health, climate adaptation, soil carbon storage,

and reduced environmental impacts associated with inefficient fertilizer use (Amanullah *et al.*, 2023).

12. Economic Importance

INM can improve economic efficiency through better use of purchased fertilizers, recycling of locally available organic materials, reduced nutrient losses, and improved soil productivity. However, economic benefits vary with the availability, nutrient content, transport cost, labor requirements, fertilizer prices, and crop value. Thus, the economically appropriate nutrient combination should be determined under local conditions.

13. Major Challenges in Adoption

- Limited farmer awareness and technical knowledge.
- Inadequate availability and variable quality of organic inputs and biofertilizers.
- High transport and labor requirements for bulky organic materials.
- Variability in nutrient content of manures and recycled wastes.
- Limited access to soil testing and site-specific recommendations.
- Differences in soil, crop, climate, irrigation, and cropping systems.
- Insufficient extension support and demonstration of INM practices.
- Need for effective quality-control systems for biological and organic inputs.
- Institutional, market, and policy constraints affecting input access and adoption.

The appropriate nutrient balance differs among locations because soil type, climate, crop, farming practice, and available technology differ. Consequently, INM requires local research, farmer participation, extension support, and adaptive recommendations rather than a single universal package (Gruhn *et al.*, 2000).

14. Practical Framework for INM

- **Step 1 – Assess soil fertility:** Use soil testing to identify nutrient status and major constraints.
- **Step 2 – Determine crop requirement:** Consider crop, variety, expected yield, season, and growing conditions.
- **Step 3 – Assess available nutrient sources:** Identify FYM, compost, crop residues, green manure, biofertilizers, and fertilizers.
- **Step 4 – Prepare a nutrient budget:** Estimate nutrient inputs and expected removal by the crop.
- **Step 5 – Select sources:** Combine nutrient sources according to requirement, availability, cost, and soil condition.
- **Step 6 – Decide timing and placement:** Apply nutrients when and where crop uptake is most effective.

- **Step 7 – Monitor crop and soil:** Observe crop performance and use soil or plant testing where appropriate.
- **Step 8 – Evaluate results:** Assess yield, nutrient-use efficiency, economic return, soil condition, and environmental effects.

15. Future Prospects

Future INM strategies are expected to combine traditional nutrient-recycling practices with modern technologies. Important areas include improved biofertilizers and microbial consortia, precision nutrient management, digital soil mapping, sensor-based diagnosis, remote sensing and UAVs, controlled-release fertilizers, improved organic waste recycling, and climate-smart nutrient management. Greater emphasis is also expected on climate-smart nutrient management practices that enhance productivity while reducing nutrient losses and environmental impacts. Mainstreaming INM will require continued research, farmer capacity building, quality input systems, extension support, and enabling policies.

Conclusion

Integrated Nutrient Management (INM) provides a comprehensive framework for achieving sustainable crop production while maintaining soil fertility and protecting environmental resources. The approach is based on the judicious combination of organic amendments, mineral fertilizers, and biological nutrient sources, with their use adjusted according to crop nutrient demand, soil characteristics, and prevailing agro-ecological conditions.

Appropriately implemented INM can improve soil fertility, enhance nutrient-use efficiency, support stable crop yields, facilitate the recycling of available nutrient resources, and reduce unnecessary nutrient losses. Its effectiveness, however, depends on several factors, including reliable soil testing, site-specific nutrient recommendations, access to quality inputs, farmer awareness and technical skills, effective extension services, regular monitoring, and appropriate systems for recycling organic resources.

The future development of INM is expected to benefit from advances in microbial inoculants, precision nutrient management, digital decision-support systems, sensor and remote-sensing technologies, improved fertilizer formulations, and climate-resilient agricultural practices. Integrating these innovations with locally adapted nutrient-management strategies can strengthen the efficiency and sustainability of agricultural production. Therefore, INM should be regarded not simply as a fertilizer-management approach but as a long-term strategy for sustaining soil health, crop productivity, resource efficiency, and the productive potential of agricultural land.

References

1. Amanullah, O. G., & Al-Tawaha, A. R. (2023). Editorial: Integrated nutrients management: An approach for sustainable crop production and food security in changing

- climates. *Frontiers in Plant Science*, 14, Article 1288030.
<https://doi.org/10.3389/fpls.2023.1288030>
2. Antil, R. S., & Raj, D. (2019). Integrated nutrient management for sustainable crop production and improving soil health. In *Nutrient dynamics for sustainable crop production*. Springer.
 3. Gruhn, P., Goletti, F., & Yudelman, M. (2000). *Integrated nutrient management, soil fertility, and sustainable agriculture: Current issues and future challenges*. International Food Policy Research Institute.
 4. Jat, L. K., Singh, Y. V., Meena, S. K., Parihar, M., Jatav, H. S., & Meena, V. S. (2015). Does integrated nutrient management enhance agricultural productivity? *Journal of Pure and Applied Microbiology*, 9(2), 1211–1221.
 5. Lal, R. (2012). Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research*, 1, 199–212.
 6. Mitter, E. K., Tosi, M., Obregón, D., Dunfield, K. E., & Germida, J. J. (2021). Rethinking crop nutrition in times of modern microbiology: Innovative biofertilizer technologies. *Frontiers in Sustainable Food Systems*, 5, Article 606815.
 7. Paramesh, V., Mohan Kumar, R., Rajanna, G. A., Gowda, S., Nath, A. J., Madival, Y., & Toraskar, S. (2023). Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Frontiers in Sustainable Food Systems*, 7, Article 1173258.
 8. Selim, M. M. (2020). Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. *International Journal of Agronomy*, 2020, Article 2821678.
 9. Sharma, T., Arya, V. M., Sharma, V., Sharma, J., Gulshan, T., Bera, A., & Laskar, Y. A. (2022). Integrated nutrient management: A long-term approach towards sustainability. *International Journal of Plant & Soil Science*, 34(20), 433–446.
 10. Tahat, M. M., Alananbeh, K. M., Othman, Y. A., & Leskovar, D. I. (2020). Soil health and sustainable agriculture. *Sustainability*, 12(12), Article 4859.
 11. Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of the Total Environment*, 512, 415–427.
 12. Yadav, K. K., Singh, A. K., Chaturvedi, S. K., Singh, S. N., Kumar, V., Gupta, P., & Gupta, S. (2025). Integrated nutrient management in sustainable agriculture: Advances and challenges. *International Journal of Plant & Soil Science*, 37(9), 314–327.
<https://doi.org/10.9734/ijpss/2025/v37i95710>



Environmental Challenges and Human Health: Integrating Science for a Sustainable Future (ISBN: 978-81-69967-17-4)



About Editors



Dr. P. Mary Anupama, M.Sc., Ph.D., PGDHRM, is Head and Assistant Professor in the Department of Biochemistry at St. Joseph's College for Women (Autonomous), Visakhapatnam. She has 22 years of teaching and 25 years of research experience. She earned her Ph.D. in Biochemistry (Biotechnology) from Andhra University in 2002, researching optimized ethanol production from pearl millet through submerged fermentation. Her qualifications include an M.Sc. in Biochemistry, a Diploma in Management, and a Postgraduate Diploma in Human Resource Management. Her research interests encompass fermentation technology, enzymology, microbiology, antimicrobial agents, bioenergy, nanotechnology, bioinformatics, and nutrition. She completed a UGC Major Research Project on violacein production and developed an economical medium and novel reactor. She has filed patents on a multi-tube reactor for enhanced cell cultivation and nanofiber applications. She has guided 15 B.Tech projects, two M.Tech projects, one M.Phil. project, and over 60 internships. Her scholarly contributions include 34 research papers, two books, and ten book chapters. She serves as a journal reviewer and editorial board member. Her honours include the Andhra Pradesh State Best Teacher Award in Biochemistry (2023), Sri V.B.V. Reddy Research Medal (2002), Academic Excellence Award (2024), and National Pride Award (2026). A Ranger Leader with the Bharat Scouts and Guides Himalaya Wood Badge, she promotes student development, scientific thinking, innovative research, and quality education.



Dr. Mousami Shankar Addala, Ph.D. in Biochemistry, has been serving as Assistant Professor at St. Joseph's College for Women (Autonomous), Visakhapatnam, since June 2019. She specializes in biochemical, biotechnological, molecular, and microbiological sciences. A DST INSPIRE Fellow (2011–2016) and doctoral researcher at CSIR-Central Food Technological Research Institute (CFTRI), Mysore, she is a double Gold Medalist from GITAM University A.Q.J. Degree College. Her research interests include resistant starch, probiotics, lactic acid bacteria, and amylolytic enzymes. She has published research papers in reputed journals and holds a published patent for a device identifying Alzheimer's disease through blood plasma proteins. She authored A Textbook of Microbiology (2025) and contributed book chapters on millets, probiotics, and women's health. Her technical expertise includes protein purification, chromatography, RT-PCR, NMR, and cell culture. She has served as Faculty Advisor for the Student Council, Entrepreneur Development Cell, and Green Audit Cell. Her awards include the Guru Brahma Award-2025 and Upadhyaya National Award.

