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Biodiversity and Environmental Sustainability: Integrating Traditional Knowledge, Science and Innovation

# Biodiversity and Environmental Sustainability : Integrating Traditional Knowledge, Science and Innovation

First Edition

**Editors**
Dr. Shiv Mahendra Singh
Rahul Kumar
Vinod Kumar Maurya



THANUJ INTERNATIONAL PUBLISHERS, TAMIL NADU, INDIA

# Biodiversity and Environmental Sustainability: Integrating Traditional Knowledge, Science and Innovation


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# About the Book

***Biodiversity and Environmental Sustainability: Integrating Traditional Knowledge, Science and Innovation*** is an interdisciplinary volume addressing contemporary issues in biodiversity conservation, environmental sustainability, natural resource management, and human well-being. The book brings together traditional ecological knowledge, scientific research, and emerging technological approaches to examine the challenges and opportunities in conserving and sustainably using biological resources.

The volume covers a broad range of themes, including wetland ecology, non-wood forest products and food security, nature-based solutions, environmental literacy, wildlife conservation, ethnobotany, medicinal plants, sustainable crops, air pollution, plant stress responses, climate resilience, and innovative approaches such as artificial intelligence and molecular techniques. It places particular emphasis on the role of indigenous knowledge and biological resources in strengthening ecological resilience, sustainable livelihoods, food and health security, and conservation practices.

By integrating perspectives from biodiversity science, ecology, botany, ethnobotany, environmental science, agriculture, biotechnology, pharmacology, and emerging technologies, this book highlights the importance of interdisciplinary approaches to address complex environmental challenges. It further emphasises the complementary role of traditional knowledge and modern scientific innovation in developing practical and sustainable solutions for biodiversity conservation and environmental management.

The book is intended as a valuable academic reference for researchers, educators, students, environmental professionals, conservation practitioners, policymakers, and readers interested in biodiversity, sustainability, traditional knowledge, and scientific innovation. It provides a contemporary and integrated perspective on the pathways towards a more resilient, sustainable, and biodiversity-conscious future.

## About Editor



**Dr. Shiv Mahendra Singh** is an Assistant Professor in the Department of Botany at Maharani Lal Kunwari Post Graduate College, Balrampur, which is affiliated with Maa Pateswari University. With over a decade of teaching experience across various academic institutions, his core areas of instruction and research span Plant Taxonomy, Biodiversity and Ecology.

Dr. Singh earned his D.Phil. in 2012 from the Department of Botany at the University of Allahabad Prayagraj. He began his career as a Project Fellow at the Centre for Social Forestry and Eco-Rehabilitation (CSFER), Prayagraj, an advanced Centre under the Indian Council of Forestry Research and Education (ICFRE), Dehradun. An active contributor to the academic community, Dr. Singh serves as a member of the Board of Studies for both Maa Pateswari University, Balrampur and Siddharth University, Kapilvastu, Siddharth Nagar. He was awarded the prestigious title of Fellow of Botanical Society (FBS) in 2021 and maintains memberships in several other scientific bodies.

As a dedicated researcher, he is the Principal Investigator for a major research project funded by UP-CST Lucknow, focusing on the assessment, conservation, and sustainable management of Non-Timber Forest Products (NTFPs) in the Sohelwa Wildlife Sanctuary. He has guided over 35 postgraduate dissertations and is currently supervising three Ph.D. scholars. His extensive publication record includes more than 19 research papers in national and international peer-reviewed journals, 20 book chapters, three edited books, and two undergraduate textbooks.

# About Editor



**Mr. Rahul Kumar** is an Assistant Professor in the Department of Botany at Maharani Lal Kunwari Post Graduate College, Balrampur, affiliated to Maa Pateswari University, Balrampur. He is actively engaged in teaching, research, and academic activities in the field of Botany and Plant Ecology in the last four years. His research work focuses particularly on understanding plant community structure, productivity, and ecological processes in Forest and grassland ecosystems. He has contributed to the scientific literature through three research papers and seven book chapters.

Mr. Kumar completed his B.Sc. from Govt. Postgraduate College, Bisalpur, Pilibhit in 2014and M.Sc. from M.J.P. Rohilkhand University Campus, Bareilly in 2016. After that he has qualified for CSIR-NET-JRF in Life Sciences in 2017. In 2018 he has got the admission in Ph.D. program through Academy of Scientific and Innovative Research (AcSIR) at CSIR-National Botanical Research Institute, Lucknow.

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He has contributed four book chapters, five abstracts, and one research paper, and has delivered oral and poster presentations at national-level seminars organized at college and university levels. He has also actively contributed to organize a National Seminar on biodiversity and ethnobotany on 22 & 23 April 2026 at M.L.K. (P.G.) College. His research interests include plant documentation, traditional botanical knowledge, biodiversity conservation, and sustainable utilization of forest resources. Alongside academic and research pursuits, Mr. Maurya has demonstrated success in competitive teaching recruitment examinations, having qualified for UP PGT (Biology) 2022 recruitment conducted in 2026, GIC Lecturer (Biology), and KVS PGT (Biology) 2025 recruitment.

# Biodiversity and Environmental Sustainability: Integrating Traditional Knowledge, Science and Innovation

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# Wetlands: Ecological Wealth for Biodiversity and Environmental Resilience

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## Abstract

Wetlands are among the most productive and ecologically varied ecosystems on the planet, offering a variety of ecological, economic, and social advantages. Wetlands, which exist in a transitional zone between terrestrial and aquatic ecosystems, support various species of plants, animals, and microorganisms while also performing important ecosystem activities like water purification, flood regulation, nutrient cycling, and climate regulation. Despite covering only, a small percentage of the Earth's surface, wetlands support a considerable portion of global biodiversity and play an important role in carbon sequestration by storing organic carbon in vegetation and soil. Wetlands also provide livelihood opportunities through fishing, agriculture, ecotourism, and other ecological services. However, increased urbanization, land-use change, pollution, eutrophication, invasive species, and climate change have all contributed to wetland degradation around the world. Rising temperatures, sea-level rise, and changing hydrological regimes threaten the ecological integrity and resilience of these ecosystems. As a result, effective conservation, restoration, and sustainable management strategies are critical for preserving wetland biodiversity and increasing environmental resilience in the face of global climate change.

**Keywords:** Wetlands, Biodiversity, Ecosystem services, Carbon sequestration; Climate change, Nutrient cycling; Water purification.

## Introduction

Wetlands are transitional areas with a unique environment that experience seasonal or permanent flooding and are dominated by oxygen-free processes (Keddy, 2010). Swamps, peat fields, sloughs, marshes, bogs, mires, and fens are different type of wetlands (Mitsch and Gosselink, 2007). The distinctive flora of aquatic plants known as hydrophytes, which are adapted to the particular hydric soil, is the main property that sets wetlands apart from other land types or bodies of water (Butler, 2010). Wetlands are among the world's most productive and biologically varied ecosystems, ranking with rain forests and coral reefs. They serve as significant biodiversity reservoirs, sustaining a wide range of species from bacteria to mammals (Dorney et al, 2010). Climate, topography (landscape shape), geology, nutrients, and hydrology (water amount and movement) all influence the plants and animals that live in wetlands. Wetlands exist naturally on all continents except Antarctica (Davidson, 2014). Wetlands contain water that is fresh, brackish, or salty. According to the

Ramsar Convention, 'Wetlands include areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including regions of sea water whose depth at low tide does not exceed six meters.' 2001). Wetland ecosystem services have the highest value per hectare of any ecosystem, and their cumulative value accounts for 47% of the world ecosystem's value (Costanza et al, 1997). As a result, it is one of the most significant and productive ecosystems (Mitsch, 1994; Smardon, 2009). Wetlands contribute to global and local/regional climate change by absorbing carbon dioxide and releasing methane, as well as by providing the atmosphere with potential or near-potential evapotranspiration (Russi et al, 2013). In terms of biodiversity, freshwater wetlands are home to more than 40% of all species on Earth, although making up only 1% of the planet's surface (Mitra et al, 2003). Wetlands maintain the crucial components of the hydrologic cycle by replenishing groundwater, controlling water flow, and purifying water (MEA, 2005). Eighty percent of the world's population relies on traditional medicines which is found in wetlands for primary healthcare (Mitra et al, 2003). The world's wetland area has been declining, and its quality has been declining because of the combined effects of natural and human factors (Brinson et al, 2002; Max Finlayson, 2012; Davidson, 2014; Gardner et al, 2015; Gardner et al, 2018). According to Davidson's startling findings, worldwide the number of wetlands has been deteriorated by over 87% since 1700 in data-existing locations, with most of this degradation taking place in the 20th and early 21st centuries (Davidson, 2014).

## Types of Wetlands and Their Biodiversity

Wetlands are diverse and can be classified into various categories, each having their own characteristics and biological communities. Understanding these categories allows us to appreciate the diverse biodiversity of these ecosystems.

### Marshes

Marshes are wetlands dominated by herbaceous plants including grasses, sedges, and reeds. They can be freshwater, brackish, or saline and are commonly found in low-lying places where water gathers. Common flora includes cattails (*Typha spp.*), bulrushes (*Schoenoplectus spp.*), and different sedge and rush species. These plants thrive in saturated soils and play an important role in stabilizing marsh soil and filtering contaminants. These places are favourable for species, including amphibians like frogs and salamanders, insects like dragonflies and mosquitoes, and a diverse range of birds like rails, herons, and ducks. Many fish species use wetlands as nursery grounds.

### Swamps

Swamps are wooded wetlands that are flooded or saturated with water for much of the year. They can be freshwater or saltwater, with trees and shrubs as the dominant

vegetation. Typical trees include cypress (*Taxodium spp*.), black gum (*Nyssa sylvatica*), and different willow species (*Salix spp.*). These plants have developed adaptations to live in wet circumstances. Swamps sustain a wide variety of wildlife, including large mammals like deer and bears, reptiles like alligators and turtles, and numerous bird species. Many animals rely on the lush greenery for habitat and food.

**Bogs**

Bogs are acidic, nutrient-poor wetlands that accumulate peat. Mosses, notably sphagnum moss, dominate these areas, which are often located in cooler regions. Bogs host a variety of special plants, including cranberry (*Vaccinium macrocarpon*), sundew (*Drosera spp.*), and heathers (*Calluna spp.*). Bogs are home to peculiar species adapted to low-nutrient environments, such as insects (e.g., bog leeches), amphibians, and birds like the bog-loving spotted sandpiper (*Actitis macularius)*.

**Mangroves**

Mangroves are coastal wetlands found in tropical and subtropical regions, distinguished by salt-tolerant trees and intricate root systems that maintain coastal soils. The key species are red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia marina*), and white mangrove (*Laguncularia racemosa*). These plants have adaptations like aerial roots and salt-secreting glands. Mangroves are important habitat for many species, including fish (e.g., snappers, groupers), crustaceans (e.g., crabs, shrimp), and birds (e.g., mangrove monitor). They also function as breeding sites for a variety of marine organisms.

## IMPORTANCE OF WETLANDS

Wetlands are vital ecosystems that support rich biodiversity and provide essential services such as water purification, flood control, groundwater recharge, and carbon sequestration.

### 1. Biodiversity

Wetlands are unique ecosystems that support a varied range of floral, faunal, and microbiological species around the world. Members of biotic communities rely on one another, and diversities vary depending on the size, shape, location, climate, water, and nutrient supplies of the wetlands. Biodiversity, which includes plants, animals, and microbes, regulates the biogeochemistry of the wetland, while changes in the physical and chemical nature of the wetlands regulate the wetlands' community structure. For surface areas of up to 4-5 ha, bird species richness was found to be positively associated. The high shoreline complexity and age of the wetlands were found to be favourably connected to the formation of high macrophytes.

**Factors that contribute to wetland biodiversity:**

Wetlands are known for their biodiversity, which is influenced by several biological and environmental factors.

- **Habitat Diversity**

**Microhabitats:** Wetlands have a variety of microhabitats such as open water, floating vegetation, submerged plants, and mudflats. Each microhabitat supports a variety of species and life stages, increasing overall biodiversity.

**Spatial Variation:** Wetlands' heterogeneous character, with variations in water depth, salinity, and substrate, creates good condition for growth of specialized plant and animal species.

- **Nutrient Cycle and Productivity**

**Primary Production:** Wetlands are extremely productive ecosystems because of their ability to absorb and recycle nutrients. Plants in wetlands grow quickly, and decomposition of organic matter helps with nutrient cycling.

**Decomposition:** Microorganisms and invertebrates break down organic matter, returning nutrients back into the soil system. This process benefits the food web by giving nutrients to both primary producers and consumers.

**Water Regulation and Hydrology:** Chloride ions have an important function in the biological balance of wetland biodiversity. As a key component of salts, they regulate water salinity levels, which alter the species makeup of wetland ecosystems. The concentration of chloride ions can influence which plant and animal species grow, as certain organisms are more tolerant of saline environments than others. In moderate proportions, chloride ions help and support various ecosystems; but, excessive chloride levels, which are frequently caused by human activities such as road salting and industrial discharge, can upset the natural equilibrium, kill sensitive species and altering biodiversity (Shukla and Arya, 2018).

**Flood Control:** Wetlands act as natural sponges, absorbing surplus water from floods and gradually releasing it. This regulation contributes to stable conditions for aquatic and terrestrial animals. Wetlands also remove pollutants and sediments from water, so increasing water quality and generating healthier environments for aquatic animals (Madhuhleka and Arya, 2016).

- **Connectivity and Buffering**

**Ecological Corridors:** Wetlands frequently connect diverse habitats, allowing species to migrate and sustain genetic variety. This link is critical for many migratory and dispersal-dependent species.

**Climate Resilience:** Wetlands help to buffer against environmental change by stabilizing coastline erosion, moderating storm impacts, and regulating microclimates.

**Threats to wetland biodiversity**

Despite their significance, wetlands face severe risks to their biodiversity and ecological functioning. Climate change and excessive anthropogenic activity are negatively impacting biodiversity (Kumar, 2021; Prakash and Verma, 2022).

Understanding these issues is critical for designing effective conservation efforts.

- **Climate Change**

Rising temperatures can affect species distributions, disrupt breeding patterns, and upset the equilibrium of wetland ecosystems. Warmer temperatures, for example, might cause higher evaporation, which affects water levels and habitat availability.

- **Sea Level Rise**

Coastal wetlands are especially sensitive to rising sea levels, which can cause habitat loss, increased salinity, and species composition changes. Mangrove forests and salt marshes are in risk of being submerged or turned into open water.

- **Habitat destruction and degradation**

**Land Conversion:** Wetlands are frequently drained or filled for agricultural, industrial, or urban purposes. The loss of habitat diminishes biodiversity and impairs ecosystem processes including water filtration and flood control.

Pollution from agricultural runoff, industrial discharge, and wastewater can introduce nutrients, heavy metals, and toxins into wetlands. These contaminants can damage water quality, endanger aquatic life, and disturb ecological processes (Madhuhleka and Arya, 2016; Singh et al, 2023).

**Invasive Species: Plant Invasions:** Non-native plant species like purple loosestrife (*Lythrumsalicaria*) and water hyacinth (*Eichhornia crassipes*) can outcompete native plants, limit habitat variety, and disrupt ecological functioning.

**Animal Invasions:** Non-native animals such as the Asian tiger, mosquito, and European carp can disrupt food webs, feed on native species, and change habitat patterns. Unsustainable activities can cause species losses and the loss of habitat functions.

- **Overexploitation**

**Resource Harvesting:** Overharvesting of wetland resources such as fish, plants, and peat can decrease populations and upset ecosystem equilibrium.

**Tourist and Recreation:** Unregulated tourist and recreational activities can cause habitat disturbance, pollution, and increased demand on wetland resources. Boating,

fishing, and off-road vehicle use can all cause damage to fragile wetland habitats (Arya, 2024).

## 1. Cabon sequestration

Global surface temperatures have risen by 0.8°C since the late nineteenth century, with 11 of the 12 warmest years on record occurring since 1995 (IPCC 2007). The Earth's average temperature is expected to rise by 1.5-5.8°C during the twenty-first century (IPCC 2001). Since 1975, global temperatures have increased at a pace of 0.15°C per decade. The twentieth century has seen a 15-23 cm rise in sea level (IPCC 2007), as well as significant changes in ecosystems (Greene & Pershing, 2007) and wildfire frequency and intensity (Running, 2006; Westerling et al, 2006). These and other observable climate changes are attributed to greenhouse gas (GHG) emissions from anthropogenic activities such as land-use change, deforestation, biomass burning, wetlands drainage, soil cultivation, and fossil fuel combustion. As a result, the concentration of atmospheric GHGs and their radiative forcing have steadily increased with human population growth, particularly since the start of the industrial revolution around 1850. Carbon dioxide ($CO_2$) concentrations have grown by 31% from 280 ppmv in 1850 to 380 ppmv in 2005, and are currently increasing at 1.7 ppmv $yr^{-1}$ (0.46% $yr^{-1}$) (WMO 2006; IPCC 2007). Methane ($CH_4$) and nitrous oxide ($N_2O$) concentrations have gradually increased within the same time period (IPCC 2001, 2007; Prather et al, 2001; WMO, 2006). According to Ramaswamy et al, 2001; the total radiative forcing of all GHGs since 1850 is calculated to be 2.43 W/m² (IPCC 2001, 2007).

From 1980 to 2000, emissions from fossil fuel burning grew by 40% (Wofsy, 2001). However, the amount of $CO_2$ accumulating in the atmosphere remained constant over this time because the excess $CO_2$ emitted is being absorbed by oceans, forests, soils, and other ecosystems (Battle et al. 2000). During the 1980s and 1995, atmospheric $CO_2$ grew at a rate of 2.8-3.0 Pg C $yr^{-1}$, and then between 3.0 and 3.5 Pg C $yr^{-1}$ from 1995 to 2005. Anthropogenic emissions of 6-8 Pg C $yr^{-1}$, together with atmospheric increases of 2.8-3.5 Pg C $yr^{-1}$, suggest the presence of significant worldwide terrestrial sinks (Fung, 2000; Pacala, 2001). The transfer and secure storage of atmospheric $CO_2$ into other long-lived C pools that would otherwise be vented or remain in the atmosphere is known as 'carbon sequestration'. As a result, in this context, C sequestration can be either natural or anthropogenic. The goal of an anthropogenically driven carbon sequestration process is to balance the global carbon budget so that future economic expansion is based on a 'C-neutral' strategy that involves no net gain in the atmospheric carbon pool. Such an approach would entail sequestering practically all anthropogenically generated $CO_2$ via safe, environmentally friendly, and stable procedures with negligible leakage risks.

**Abiotic sequestration.**

Abiotic sequestration relies on physical and chemical interactions, as well as engineering techniques, and does not include live creatures. Rapid progress is being made in the development and testing of $CO_2$ capture, transport, and injection devices (Kerr, 2001).

**Biotic sequestration**

Biotic sequestration is the controlled intervention of higher plants and microorganisms in removing $CO_2$ from the atmosphere. It differs from management approaches that reduce or offset emissions. Another strategy for regulating the terrestrial C pool is to increase resource efficiency (for example, water and energy).

**Oceanic sequestration**

Several biological processes, including photosynthesis, contribute to carbon sequestration in the ocean. Phytoplankton photosynthesis fixes about 45 Pg C per year (Rivkin & Legendre, 2001; Falkowski et al, 2000). It is also suggested that incremental C could be offered as credits in the emerging global C market.

**Terrestrial sequestration**

Terrestrial sequestration refers to the transfer of atmospheric $CO_2$ into biotic and pedologic carbon reservoirs. Only 40% of the $8.6\,\mathrm{Pg\,C\,yr^{-1}}$ emitted into the atmosphere ($3.5\,\mathrm{Pg}$) remains due to unidentified terrestrial sinks that trap atmospheric $CO_2$ and play a key role in the global carbon cycle. Terrestrial ecosystems are a substantial carbon sink due to photosynthesis and $CO_2$ storage in live and dead organic matter. Terrestrial carbon sequestration is frequently referred to as a win-win or no-regrets method due to its multiple ancillary advantages (such as enhanced soil and water quality, restoration of degraded ecosystems, and increased crop productivity) (Lal et al, 2003). Forest ecosystems retain carbon in the form of lignin and other relatively resistant polymeric carbon molecules. Forest carbon is trapped not just in harvestable timber, but also in woody waste, wood products, and other woody plants that encroach on grasslands (Wofsy, 2001). Afforestation is a potential alternative for carbon sequestration in terrestrial ecosystems (IPCC, 1999; Fang et al, 2001; Lamb et al, 2005). Restoration of degraded tropical forests is another major approach (Lamb et al, 2005). According to Pacala and Socolow's (2004) estimates, managing temperate and tropical forests is one of 15 alternatives for stabilizing atmospheric $CO_2$ concentrations at 550 ppm by 2050.

**Soil carbon sequestration**

The implications of soil carbon sequestration include increasing the concentration/pools of SOC and SIC as secondary carbonates through land-use conversion and the implementation of recommended management practices (RMPs) in

agricultural, pastoral, and forestry ecosystems, as well as restoring degraded and severely disturbed soils. Another alternative is to make charcoal and utilize biochar as fertilizer (Fowles, 2007). In general, farmed soils retain 50-75% of the initial SOC pool. Oxidation/mineralization, leaching, and erosion all contribute to the depletion of SOC pools. In addition to organic carbon storage, soil carbon sequestration can take place in the form of soil inorganic carbon (SIC), primarily as secondary carbonates and dissolved bicarbonates transported into groundwater. Secondary carbonates exist in a variety of forms, including films, threads, concretions, and pedants. There are four main pathways for secondary carbonate production (Monger, 2002; Mermut& Landi, 2006). According to Monger, 2002; pedogenic/secondary carbonates are biogenic in origin and generated by soil fauna (for example, termites).

## I. Nutrient Removal

Wetlands provide vital ecological services such as nutrient removal. The removal of nutrients delivered to water from landscapes or other resources minimizes the nutrient load in rivers and oceans, thereby protecting their natural habitats. As a result, they conserve their natural biodiversity while also remaining useful for ecological and economic benefits. According to Saunders and Kalff, 2001; wetlands have the highest nitrogen retention capability, followed by lakes and rivers, respectively. According to Lucassen et al, 2005, groundwater impacted by events such as dam construction, drought, and agricultural water collection is the primary source of orthophosphate in wetlands, while leaching from agricultural land and forest soils is an important source of nitrate. Fisher and Acreman, 2004; found that riparian wetlands remove more total N and P than swamps and marshes, whereas swamps and marshes remove more ammonium-N and soluble P. It was also said that the oxygen concentration in sediment, redox measurement, degree of waterlogged condition, hydraulic retention, and vegetation processes all influence N and P removal in wetlands.

## II. Water Quality

Aside from nutrient removal, wetlands can reduce water contamination caused by heavy metals, excess sediments, faecal microorganisms, and xenobiotics. They keep the water quality at a level that does not harm biodiversity, protects human health, and makes the water reusable for a variety of applications, including agriculture. Wetlands can successfully remove heavy metals from water using chemical, physical, and biological processes. According to Sheoran and Sheoran, 2006; heavy metals can be removed through chemical processes such as adsorption to clay and organic matter, hydrolysis and/or oxidation, precipitation, carbonate and sulphide formation, as well as biological processes such as plant uptake, bacterial sulphate metabolism, and iron reduction. All of these activities are not independent; rather, they are reliant on the pH, ions, organic matter, and a variety of other wetlands characteristics. The majority of the heavy metals found in wetlands are Fe, Al, Mn, Cu, Ni, Zn, Mn, Pb, and Cd.

Similar processes can remove a large number of them, or they may go through distinct removal mechanisms depending on the external conditions. Cu, Mn, Mo, Ni, V, and Zn co-precipitate with iron oxides, whereas Co, Fe, Ni, Pb, Zn, and Co co-precipitate with manganese oxides, and organic matter such as humic, tanic, and fulvic acid eliminates heavy metals through complex formation (Matagi et al, 1998). Plants can effectively remove metal from wetlands. *E. rasmosisti* effectively removes Pb and Zn, while *E. ralleculosa* removes Cu (Deng et al, 2004). Prasad, 2003 mentions phytostabilization by lignification and humification, phytovolatilization of highly volatile elements such as mercury and selenium, and rhizofiltraionby accumulating heavy metals on root and shoots or precipitation through plant exudates are important mechanisms of metal removal from wetland soils.

Wetlands slow the flow of water, allowing suspended solids to settle. Wetlands having longer residency times do better at removing suspended particles. Bacterial decomposition of organic materials has the potential to reduce both Biological Oxygen Demand (BOD) and Chemical Oxygen Demand. Wetlands can minimize pathogenic bacteria in water by preventing their survival without a host organism. They also highlighted that delaying the flow of water can help to remove xenobiotic organic chemicals after they reach wetlands. The chemicals are then eliminated through sorption on sediments, hydrolysis, and anaerobic decomposition. Yu et al, 2005 demonstrated that autochthonous microorganisms in mangrove soil may successfully eliminate polycyclic aromatic hydrocarbons (PAHs).

## ECONOMIC IMPORTANCE OF WETLAND

Wetlands are used for a variety of purposes, including ecotourism, fuel wood gathering, agricultural water supply, and fishing. The local shrimp-fishery industry is entirely dependent on the juveniles of three species of penaeid shrimp that live in the coastal marsh of the Gulf of Mexico (Engle, 2011). Kerala, Goa, Odisha, Jammu and Kashmir, Assam, Bihar, Andhra Pradesh, and Gujarat are among the states in India where wetland-dependent fisheries are common (Bassi et al, 2014). Numerous wetlands in India are popular tourist destinations. Odisa's Chilka Lake, Kerala's backwaters, and Kutch's Small Run are just a few of the wetland-based tourist destinations that draw both domestic and foreign visitors. In these areas, tourism is one of the main sources of revenue for the local people (Bassi et al, 2014).

In addition to providing resources for economic growth, wetlands may successfully safeguard the lives and property of coastal populations. According to Bassie et al, 2014; the Bhitarkanika mangrove in Odisha, India, is effective at preventing cyclones and safeguarding nearby residents. Mangroves can lessen the impact of waves on shorelines and prevent soil erosion, according to a study by Hashimet& Catherine, 2013. Wetlands can provide the freshwater needed for farming. Greenway, 2005

found that manmade wetlands can efficiently extract nutrients from water, which can then be used for irrigation on golf courses, agriculture, and numerous other locations.

## MAJOR CAUSES OF VULNERABILITY OF WETLANDS

Numerous natural and man-made factors are endangering the wetlands' survival, diminishing their ecosystem services, and impacting their biodiversity. Pollution, eutrophication, and other threats already exist, but climate change is a slowly but steadily growing threat. Both the causes and the consequences may be independent or reliant on one another. Here, some of the risks identified by studies conducted by researchers worldwide have been described.

One of the main issues facing researchers worldwide is climate change. Temperature fluctuations, snowmelt, a surge in catastrophic events, disease outbreaks, and many other aspects are already being affected. Wetlands have a significant role in controlling the global climate since they are significant carbon sinks. However, they are also susceptible to the effects of climate change.

The wetlands' biogeochemistry, ecology, and physical characteristics may be impacted by climate change. Erwin, 2009 detailed several potential impacts of climate change on wetlands. Sea level rise will have an impact on mangroves; sea grass and marine aquatic beds will be susceptible to increased salinity; salt marshes and intertidal marshes will be threatened by sea level rise and coastal squeezing; Arctic and tundra wetlands will be affected by longer summers and higher evaporation rates; and peatlands will be affected by melting permafrosts and desertification. Sea level rise may have an impact on delicate biotic ecosystems, and variations in precipitation, evaporation, and transpiration may change the wetlands' dimensions (Brander et al, 2012).

### Land Use Change and Biodiversity Loss

One of the anthropogenic factors endangering wetlands' survival is land use change, which is widespread worldwide. Reclamation of wetlands for agriculture, urbanization, and other economic uses, overuse of wetland resources, disruption of biodiversity, and many more methods are examples of land use changes. These processes have one or more effects on biodiversity, soil fertility, hydrological balance, and wetland ecosystem services. According to Gibbons et al, 2000; the two main factors contributing to the global reduction of amphibian and reptile species are the draining of wetlands and pollution from agricultural runoff. According to Prasad et al, 2002; organic and inorganic contaminants from shrimp farms are harming Indian mangroves. Local biodiversity has also been severely harmed by the arrival of invasive species, such as *E. crassipes* and *S. moletsa*, which are endangering India's native water vegetation. Overuse of groundwater in West Bengal has decreased the amount of water supplied by aquifers to the regional wetlands, which consequently

has an adverse effect on the wetlands' continued existence (Bassie et al, 2014). Wetlands can be prevented from naturally flooding their surroundings by removing water from them and artificially raising the surrounding land. This may ultimately result in higher salinity and decreased soil fertility (Prasad et al, 2002). The expansion of road infrastructure and more accessibility to mangroves may cause the mangrove ecosystem to become more fragmented, which would lessen the protection they provide to the coastal region (Brander et al, 2002). The main invasive plants in wetlands are grasses, graminoids, forbs, shrubs, and trees. Disturbances, wetness, and nutrient buildup can control species invasion (Zedler & Kercher, 2004). Human activity is increasing the number of grass species and decreasing the number of tree species in Ghana's coastal wetlands; the process can be controlled by wildfire, herbivory, dispersal, and rainfall (Wuver et al, 2003).

**Pollution**

Anthropogenic pollution may have begun as soon as humans discovered how to use fire. Today's society depends on extensive agriculture, animal husbandry, industry, automobiles, and numerous other elements, all of which contribute to global pollution. Untreated sewage, waste dumping, industrial wastewater, runoff from agricultural fields, highways, excessive use of synthetic chemicals in homes and businesses, etc. are the main sources of pollution in wetlands. Both point and non-point sources can cause pollution; however non-point sources are more common. According to Bassie et al, 2014; eutrophication caused by untreated sewage water in the Himalayan wetlands is causing a sharp decline in dissolved oxygen (DO) and an increase in BOD. Boone & James, 2003 found that while the herbicide atrazine decreased the chlorophyll of algal species, prolonged the larval phase of small mouth larvae, and decreased the mass of toads and leopard frogs, insecticides like carbaryl can kill salamander larvae and cause reproductive failure and population decline in carnivorous salamanders. Relyea, 2009 studied impact of different insecticides and showed, carbaryl and malathion affects cladocerans, chlorpyrifos reduces the population of cladocerans and periphyton, diazinon directly affected the periphytons and indirectly reduced growth of the leopard frog tadpoles and endosufun reduces population of copepods and periphytons. Mn concentrations in the muscles of fish raised in the eastern Kolkata wetlands were found to be significantly higher than the FAO/WHO acceptable limits in a study conducted by Kumar et al, 2011.

According to Purvaja & Ramesh's, 2001 study on coastal wetlands in South India, pollution from human settlements can make these wetlands a greater source of methane, which could change the global carbon budget. According to research by Harikumar et al, 2009, Vembanad Lake has moderate levels of heavy metal pollution for Cu, moderate to high levels for Zn and Ni, and non-polluted to moderate levels for Pb. According to Xiao et al, 2014; the Pearl River estuary is seeing an increase in

PAHs due to industrial and maritime operations, and several PAH types are observed to be tightly bonded to organic matter in the soil. Due to the increasing urbanization and economic growth in the coastal regions, the concentration of PAHs in the wetland soils of the Sundarban region of India is low to moderately contaminated (Domínguez et al, 2010).

**Eutrophication**

As was previously mentioned, wetlands naturally draw nutrients out of the water. Urbanized and agricultural areas are the main suppliers of nitrogen and phosphorus in wetlands, while internal eutrophication can happen in wetlands because of anaerobic organic matter decomposition in an alkaline environment with a high concentration of sulphur dioxide (Smolders et al, 2006). Lucassen et al, 2005 state that eutrophication is likely to happen in wetlands where sulfate is transported by FeSx or nitrate concentrations are higher than sulfate. According to Houlahan et al, 2006; one of the major causes of eutrophication is the use of agricultural fertilizers, which can alter community structure and reduce the diversity of plant species. The risk of *Riberioria miracidia* in snails and amphibian larvae is indirectly increased by eutrophication; in particular, an increase in the parasite infection causes severe limb deformity and amphibian mortality (Johnson et al, 2007). According to Nyenje et al, 2010; wastewater discharge in wetlands is causing eutrophication, which is causing fish extinction, dissolved oxygen depletion, and an increase in the number of cyanobacteria and *C. botulinum* in sub-Saharan wetlands. Algae and lemnids proliferate as P levels rise (Lucassen et al, 2005).

**Discussion**

Wetlands are complex and dynamic ecosystems that support high levels of biodiversity and provide essential ecosystem services. Wetlands, with their distinct hydrological conditions, various habitats, and high biological productivity, can support a vast range of flora, fauna, and microbial populations. The cohabitation of marshes, swamps, bogs, mangroves, and other wetland types increases habitat variability, which supports species diversity and ecological stability.

Wetlands serve important ecological tasks such as nutrient cycling and water filtration. Wetland vegetation and microbial populations remove surplus nutrients, sediments, heavy metals, and contaminants from water bodies, improving water quality and preserving ecosystem health. Furthermore, it also regulates hydrological processes by serving as natural sponges, storing floodwaters, replenishing groundwater, and mitigating the effects of droughts and extreme weather.

Wetlands also help to regulate the climate by sequestering carbon. Wetland soils and vegetation store a lot of carbon, which lowers atmospheric $CO_2$ levels and helps to slow global warming. However, human-caused disturbances such as wetland drainage,

land conversion, industrialization, pollution, and unsustainable resource extraction have drastically impacted wetland extent and functionality. Climate change exacerbates these stresses through sea-level rise, shifting precipitation patterns, and rising temperatures.

Wetlands' increasing vulnerability emphasizes the critical need for integrated conservation approaches such as habitat restoration, pollution management, long-term land-use planning, and community participation. Strengthening scientific research, policy implementation, and public awareness will be critical to preserving wetland biodiversity and ensuring long-term environmental resilience.

**Conclusion**

Wetlands are valuable ecological assets that support biodiversity, control hydrological and biogeochemical cycles, and provide several ecosystem services critical to human well-being. Their ability to trap carbon, clean water, alleviate floods, and support diverse biological ecosystems makes them essential components of global environmental resilience. However, growing anthropogenic pressures and climate change pose significant challenges to the structure and function of wetland ecosystems.

To protect and restore wetlands, governments, scientists, local communities, and international organizations must work together. Sustainable management techniques, supported by adequate scientific understanding and effective regulatory frameworks, are required to protect wetland resources for future generations. Recognizing wetlands as ecological wealth is essential for achieving biodiversity conservation, climate change mitigation, and sustainable development goals in the twenty-first century.

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# Ethnobotanical Study of Anti-inflammatory Plants

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## Abstract

Inflammation is a complex biological response associated with numerous acute and chronic diseases, including arthritis, cardiovascular disorders, diabetes, cancer, and neurodegenerative conditions. Since ancient times, medicinal plants have been widely utilized in traditional healthcare systems for the treatment of inflammatory ailments. Ethnobotany provides a scientific framework for documenting indigenous knowledge related to medicinal plant use and offers valuable insights for the discovery of novel therapeutic agents. This chapter presents an ethnobotanical overview of anti-inflammatory plants used by various indigenous and rural communities across different geographical regions. It highlights traditional knowledge regarding plant species, local names, plant parts utilized, modes of preparation, dosage forms, and therapeutic applications. Furthermore, the chapter discusses major phytochemical constituents such as flavonoids, phenolics, alkaloids, terpenoids, tannins, and saponins that contribute to anti-inflammatory activity. Emphasis is also given to pharmacological validation, mechanisms of action, and recent scientific advancements supporting traditional claims. Important medicinal plants including *Curcuma longa*, *Azadirachta indica*, *Withania somnifera*, *Zingiber officinale*, and *Boswellia serrata* are discussed as representative ethnomedicinal species with proven anti-inflammatory potential. The chapter further addresses issues related to conservation of medicinal flora, sustainability of traditional knowledge, bioprospecting, and challenges in standardization and clinical validation of herbal medicines. Overall, this chapter underscores the significance of ethnobotanical research in bridging traditional medicine and modern pharmacology for the development of safer and effective anti-inflammatory therapeutics.

**Keywords:** Ethnobotany, Anti-inflammatory plants, Medicinal plants, Traditional medicine, Phytochemicals, Herbal therapy, Indigenous knowledge, Pharmacological validation

## Introduction

Inflammation is a complex biological response of living tissues against harmful stimuli such as pathogens, damaged cells, toxins, allergens, and physical injury. It represents a protective mechanism initiated by the immune system to eliminate injurious agents and promote tissue repair and healing (Medzhitov, 2008; Ferrero-Miliani et al., 2007). The inflammatory response involves a series of coordinated vascular, cellular, and molecular events characterized by redness, heat, swelling, pain, and loss of function (Abbas et al., 2018). Although inflammation is fundamentally beneficial and essential for survival, uncontrolled or prolonged inflammatory responses may contribute to the development of various chronic and degenerative diseases (Nathan and Ding, 2010). In recent years, inflammation has gained considerable attention because of its close association with disorders such as arthritis, diabetes, cardiovascular diseases, asthma, inflammatory bowel disease, neurodegenerative diseases, and cancer (Furman et al., 2019).

Inflammation can generally be classified into two major types: acute inflammation and chronic inflammation. Acute inflammation is a rapid and short-term response that occurs immediately after tissue injury or infection. It is characterized by increased blood flow, migration of leukocytes, and release of inflammatory mediators aimed at removing harmful stimuli and restoring tissue homeostasis (Kumar et al., 2021). Acute inflammation usually lasts for a few hours to several days and is considered a normal defense mechanism of the body. Common examples include inflammation caused by cuts, burns, infections, or insect bites. In contrast, chronic inflammation is a prolonged inflammatory condition that may persist for months or even years due to continuous exposure to irritants, autoimmune reactions, persistent infections, or metabolic disorders (Chen et al., 2018). Chronic inflammation often results in tissue destruction, fibrosis, and impaired organ function. Unlike acute inflammation, chronic inflammation is frequently associated with severe pathological consequences and is

recognized as a major contributor to several non-communicable diseases worldwide (Libby, 2007).

The global burden of inflammatory diseases has increased significantly over the past few decades, posing serious challenges to healthcare systems and public health (GBD 2019 Diseases and Injuries Collaborators, 2020). According to various health reports, chronic inflammatory disorders are among the leading causes of morbidity and mortality worldwide. Diseases such as rheumatoid arthritis, osteoarthritis, asthma, cardiovascular diseases, obesity-related inflammation, and autoimmune disorders affect millions of people and substantially reduce quality of life (Hunter, 2011). Furthermore, modern lifestyle factors including unhealthy diet, stress, pollution, smoking, sedentary behavior, and aging populations have accelerated the prevalence of inflammation-associated disorders (Furman et al., 2019). Although synthetic anti-inflammatory drugs such as non-steroidal anti-inflammatory drugs (NSAIDs) and corticosteroids are widely used for treatment, their prolonged use is often associated with adverse side effects including gastrointestinal irritation, liver toxicity, renal dysfunction, and immunosuppression (Wallace, 2008). Consequently, there is growing interest in safer and more effective natural alternatives derived from medicinal plants.

Medicinal plants have been used since ancient times in traditional healthcare systems for the prevention and treatment of various inflammatory conditions (Fabricant and Farnsworth, 2001). Traditional systems of medicine such as Ayurveda, Unani, Siddha, Traditional Chinese Medicine, and indigenous folk practices rely heavily on plant-based remedies for managing pain, swelling, fever, wounds, and inflammatory diseases (WHO, 2019). The therapeutic efficacy of medicinal plants is primarily attributed to the presence of bioactive phytochemicals including flavonoids, phenolics, alkaloids, terpenoids, tannins, and saponins, many of which possess remarkable anti-inflammatory and antioxidant properties (Rates, 2001). Several important medicinal plants such as Curcuma longa, Zingiber officinale, Withania somnifera, and Boswellia serrata have been scientifically validated for their anti-inflammatory potential and are increasingly incorporated into modern herbal formulations and nutraceutical products (Ammon, 2016; Gupta et al., 2013).

In this context, ethnobotany plays a crucial role in documenting and understanding the traditional knowledge associated with medicinal plant use. Ethnobotany is the scientific study of the relationships between human societies and plants, particularly focusing on how plants are utilized for medicine, food, rituals, and other cultural practices (Cotton, 1996). Ethnobotanical investigations provide valuable information regarding indigenous medicinal knowledge, modes of herbal preparation, plant parts used, dosage patterns, and therapeutic applications (Martin, 1995). Such studies serve as an important foundation for pharmacological screening, phytochemical analysis, and drug discovery programs (Heinrich and Gibbons, 2001). Moreover, ethnobotanical research contributes significantly to biodiversity conservation, sustainable utilization of medicinal resources, and preservation of traditional knowledge systems that are rapidly declining due to urbanization and cultural transformation (Jain, 1991). The exploration of ethnobotanical anti-inflammatory plants has become increasingly important in modern biomedical research. Traditional medicinal knowledge offers a vast repository of potentially bioactive plant species that may lead to the development of novel anti-inflammatory drugs with fewer side effects (Fabricant and Farnsworth, 2001). Therefore, integrating ethnobotanical wisdom with contemporary scientific approaches can provide promising opportunities for discovering safe, affordable, and sustainable therapeutic agents for the management of inflammatory diseases.

**Ethnobotany and Ethnomedicine**

The relationship between humans and plants has existed since the beginning of civilization. Plants have served as essential resources for food, shelter, clothing, medicine, rituals, and cultural practices. Traditional societies across the world developed extensive knowledge regarding the identification, collection, preparation, and therapeutic use of plants through continuous interaction with nature. This accumulated indigenous knowledge forms the foundation of ethnobotany and ethnomedicine, two important interdisciplinary fields that connect biological sciences with cultural and medical traditions (Balick and Cox, 1996). In recent decades, these fields have gained considerable scientific importance because of their role in

biodiversity conservation, healthcare improvement, and discovery of novel bioactive compounds from medicinal plants (Cotton, 1996).Ethnobotany and ethnomedicine provide valuable insights into traditional healthcare systems practiced by indigenous and rural communities. Such systems are often based on centuries of empirical observations and experiences passed orally from one generation to another. Many modern pharmaceutical drugs have originated from traditional medicinal knowledge, demonstrating the scientific relevance of these disciplines (Fabricant and Farnsworth, 2001). The study of ethnobotanical and ethnomedicinal practices has therefore become an important area of research for understanding plant-based therapies and identifying new therapeutic agents for various diseases, including inflammatory disorders.

## Definition and Scope

### Ethnobotany

Ethnobotany is the scientific study of the interactions and relationships between humans and plants within specific cultural and environmental contexts. The term "ethnobotany" was first introduced by the American botanist John William Harshberger in 1895 to describe the study of plants used by indigenous people (Harshberger, 1896). Ethnobotany encompasses the investigation of how different communities perceive, manage, utilize, and conserve plant resources for food, medicine, agriculture, construction, rituals, dyes, cosmetics, and other socio-cultural purposes.

The scope of ethnobotany is broad and multidisciplinary, integrating concepts from Botany, anthropology, ecology, pharmacology, taxonomy, sociology, and environmental science (Martin, 1995). Ethnobotanical studies involve field surveys, interviews with traditional healers and local inhabitants, plant collection and identification, documentation of indigenous knowledge, and analysis of plant utilization patterns. One of the major objectives of ethnobotany is to preserve traditional plant knowledge that is rapidly disappearing due to modernization, urbanization, and changing lifestyles (Jain, 1991).

Ethnobotanical research has contributed significantly to medicinal plant exploration and drug discovery. Numerous medicinal plants traditionally used by local communities have been scientifically validated for their pharmacological activities (Heinrich and Gibbons, 2001). Plants such as *Curcuma longa*, *Azadirachta indica*, and *Tinospora cordifolia*are important examples of ethnobotanically significant species widely used in traditional healthcare systems.

**Ethnomedicine**

Ethnomedicine refers to the study of traditional medical practices, beliefs, and healthcare systems developed by different ethnic and cultural groups. It focuses on how indigenous communities understand disease causation, diagnosis, prevention, and treatment using natural resources, spiritual practices, and culturally accepted healing methods (Foster and Anderson, 1978). Ethnomedicine includes the use of medicinal plants, animal products, minerals, dietary therapies, massage, rituals, and spiritual healing practices.The scope of ethnomedicine extends beyond herbal medicine and includes the cultural interpretation of health and illness. Different communities often possess unique therapeutic approaches based on their ecological surroundings, religious beliefs, and social traditions. Ethnomedicinal knowledge is generally transmitted orally through generations by traditional healers, herbal practitioners, village elders, and tribal communities (WHO, 2013).Medicinal plants constitute one of the most important components of ethnomedicine. Traditional healers utilize various plant parts such as roots, leaves, bark, flowers, fruits, and seeds for preparing decoctions, infusions, powders, pastes, oils, and extracts to treat different ailments. Many ethnomedicinal plants possess scientifically proven pharmacological activities including anti-inflammatory, antimicrobial, antioxidant, antidiabetic, anticancer, and immunomodulatory effects (Rates, 2001). Consequently, ethnomedicine serves as a valuable source for modern pharmaceutical research and development.The increasing global demand for herbal medicines and natural products has enhanced the importance of ethnomedicinal studies in identifying safer and cost-effective therapeutic agents. Furthermore, ethnomedicine contributes significantly to primary healthcare, especially

in rural and economically disadvantaged regions where access to modern medical facilities is limited (WHO, 2019).

**Indigenous Healthcare Systems**

Indigenous healthcare systems are traditional systems of healing developed by native and local communities based on accumulated cultural knowledge, practical experiences, and natural resource utilization. These healthcare systems rely primarily on locally available medicinal plants and traditional healing methods for maintaining health and treating diseases. Indigenous medical practices have existed for thousands of years and continue to play an essential role in the healthcare of millions of people worldwide (Mahomoodally, 2013).Several traditional healthcare systems are recognized globally for their therapeutic importance. In India, major indigenous healthcare systems include Ayurveda, Siddha, Unani, folk medicine, and tribal medicine. Ayurveda, one of the oldest systems of medicine, utilizes numerous medicinal plants and holistic approaches for disease prevention and treatment. Similarly, Traditional Chinese Medicine, African traditional medicine, and Native American healing systems represent important indigenous medical traditions practiced in different parts of the world (Mukherjee and Wahile, 2006).Indigenous healthcare systems are particularly important in remote and rural areas where modern healthcare infrastructure is inadequate or inaccessible. Traditional healers often serve as the primary healthcare providers for local communities. These systems are generally considered affordable, culturally acceptable, and closely connected with local biodiversity and ecological knowledge (Kala et al., 2006).Despite their importance, indigenous healthcare systems face several challenges including habitat destruction, overexploitation of medicinal plants, loss of traditional knowledge, lack of scientific validation, and inadequate documentation. Therefore, systematic ethnobotanical and ethnomedicinal studies are essential for conserving traditional knowledge and promoting sustainable utilization of medicinal plant resources.

In recent years, integration of indigenous knowledge with modern scientific research has gained considerable attention. Scientific validation of traditional medicinal

practices through phytochemical, pharmacological, and clinical studies may contribute to the development of novel plant-based therapeutics with improved safety and efficacy. Thus, ethnobotany and ethnomedicine continue to serve as important bridges between traditional wisdom and contemporary healthcare research.

**Importance of Ethnobotanical Documentation**

Ethnobotanical documentation plays a vital role in preserving the valuable traditional knowledge associated with the use of plants by indigenous and local communities. Since ancient times, human societies have relied extensively on plant resources for food, medicine, shelter, rituals, and cultural practices. Much of this traditional knowledge has been transmitted orally from one generation to another and is therefore highly vulnerable to loss due to modernization, urbanization, migration, deforestation, and changing lifestyles (Jain, 1991; Cotton, 1996). Systematic ethnobotanical documentation helps preserve this cultural heritage by recording information regarding medicinal plant species, local names, therapeutic uses, preparation methods, and modes of administration. Such documentation not only safeguards indigenous wisdom but also recognizes the intellectual contributions of tribal and rural communities to healthcare and biodiversity conservation (Martin, 1995).One of the most significant contributions of ethnobotanical documentation is its role in drug discovery and development. Traditional medicinal knowledge has historically served as an important source for identifying bioactive compounds and developing modern pharmaceuticals. Numerous plant-derived drugs used in contemporary medicine, such as aspirin, quinine, morphine, artemisinin, and vincristine, originated from ethnobotanical leads and traditional healing practices (Fabricant and Farnsworth, 2001). Ethnobotanical surveys provide researchers with valuable information regarding plants that possess therapeutic potential, thereby reducing the time and cost involved in random screening of plant species for pharmacological activities (Heinrich and Gibbons, 2001). Medicinal plants used traditionally for inflammatory disorders, infections, diabetes, cancer, and neurological diseases are increasingly being subjected to phytochemical and pharmacological investigations. Therefore, ethnobotanical knowledge serves as an important bridge between traditional medicine and modern

drug discovery programs. Ethnobotanical documentation also contributes significantly to sustainable healthcare systems, particularly in developing countries where access to modern medical facilities is limited. According to the World Health Organization, a large proportion of the global population depends on traditional plant-based medicines for primary healthcare needs (WHO, 2019). Indigenous healthcare systems are generally affordable, culturally acceptable, and locally accessible, making them highly relevant for rural and economically disadvantaged populations. Documentation of medicinal plant knowledge promotes the sustainable utilization of natural resources and encourages the conservation and cultivation of important medicinal species (Kala et al., 2006). Furthermore, integrating ethnobotanical knowledge with scientific validation can support the development of safer, eco-friendly, and cost-effective herbal therapeutics. In recent years, increasing concerns regarding the side effects of synthetic drugs and the emergence of drug resistance have further highlighted the importance of plant-based traditional medicine in achieving sustainable healthcare solutions.

In addition to healthcare benefits, ethnobotanical documentation contributes to biodiversity conservation and environmental sustainability. Traditional communities often possess extensive ecological knowledge regarding the harvesting, cultivation, and management of medicinal plants. Proper documentation of such practices can support conservation strategies and sustainable resource management programs (Balick and Cox, 1996). Thus, ethnobotanical documentation not only preserves traditional wisdom but also provides valuable scientific, medicinal, ecological, and socio-economic benefits for present and future generations.

**Plant-Derived Phytochemicals Showing Anti-Inflammatory Activity**

| Phytochemical | Source Plant (Botanical Name) | Plant Part | Reported Anti-Inflammatory Activity | References |
|---|---|---|---|---|
| Curcumin | Turmeric (*Curcuma longa* L.) | Rhizome | Inhibits NF-κB, COX-2, LOX, TNF-α, IL-1β, and IL-6 pathways. | Furst and Zundorf, 2014 |

| Phytochemical | Source Plant (Botanical Name) | Plant Part | Reported Anti-Inflammatory Activity | References |
|---|---|---|---|---|
| Gingerol | Ginger (*Zingiber officinale* Roscoe) | Rhizome | Suppresses COX and LOX enzymes and inhibits NF-κB signaling. | Rasheed and Gruber, 2025 |
| Quercetin | *Allium cepa* L. (onion), *Malus domestica* Borkh. (apple) | Bulb/Fruit | Potent flavonoid with antioxidant and anti-inflammatory activity via cytokine suppression. | Nakadate et al., 2025 |
| Epigallocatechin gallate (EGCG) | *Camellia sinensis* (L.) Kuntze | Leaves | Inhibits NF-κB, COX-2, iNOS, and inflammatory mediators. | Nakadate et al., 2025 |
| Boswellic acids (AKBA) | *Boswellia serrata* Roxb. ex Colebr. | Resin | Selective 5-LOX inhibitor reducing leukotriene synthesis. | Furst and Zundorf, 2014 |
| Resveratrol | *Vitis vinifera* L. | Fruit skin/Seeds | Reduces oxidative stress and inflammatory cytokines. | Mueller et al., 2010 |
| Luteolin | *Apium graveolens* L. (celery), *Capsicum annuum* L. | Leaves/Fruit | Suppresses inflammatory mediators and oxidative stress. | Mueller et al., 2010 |
| Lycopene | *Solanum lycopersicum* L. | Fruit | Reduces inflammation associated with obesity and chronic disorders. | Pan et al., 2010 |
| Lutein | *Spinacia oleracea* L., *Brassica oleracea* var. *acephala* | Leaves | Exhibits antioxidant and anti-inflammatory effects. | Dias et al., 2010 |
| Berberine | *Berberis aristata* DC. | Root/Bark | Inhibits inflammatory cytokines and oxidative stress pathways. | Recio et al., 2012 |

| Phytochemical | Source Plant (Botanical Name) | Plant Part | Reported Anti-Inflammatory Activity | References |
|---|---|---|---|---|
| Andrographolide | *Andrographis paniculata* (Burm.f.) Nees | Whole plant/Leaves | Demonstrates anti-inflammatory and immunomodulatory activity. | Lorden et al., 2025 |
| Catechin | *Acacia catechu* (L.f.) Willd. | Bark/ Heartwood | Flavonoid with antioxidant and anti-inflammatory activity. | Lorden et al., 2025 |
| Azadirachtin | *Azadirachta indica* A. Juss. | Seeds/Leaves | Exhibits anti-inflammatory and immunomodulatory properties. | Chen et al., 2018 |
| Emodin | *Cassia angustifolia* Vahl | Leaves/Pods | Anthraquinone compound with anti-inflammatory effects. | Chen et al., 2018 |
| Paeonol | *Paeonia suffruticosa* Andrews | Root bark | Suppresses MAPK and NF-κB signaling pathways. | Chen et al., 2018 |
| Rosmarinic acid | *Salvia officinalis* L. | Leaves | Inhibits COX-2 and NF-κB pathways. | Singh and Aggarwal, 1995 |
| Salicin | *Populus* spp. | Bark | Inhibits prostaglandin synthesis and COX enzymes. | Scotton et al., 2024 |
| Phyllanthin | *Phyllanthus amarus* Schumach. & Thonn. | Whole plant | Exhibits antioxidant and anti-inflammatory activity. | Maldini et al., 2020 |
| Rutin | *Phyllanthus amarus* Schumach. & Thonn. | Whole plant | Flavonoid with anti-inflammatory and antioxidant properties. | Maldini et al., 2020 |
| Gallic acid | *Phyllanthus amarus* Schumach. & Thonn. | Whole plant | Bioavailable phenolic acid with anti-inflammatory activity. | Maldini et al., 2020 |

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# NON-WOOD FOREST PRODUCTS AND FOOD SECURITY IN SOHELWA WILDLIFE SANCTUARY, UTTAR PRADESH

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**Abstract**

Non-Wood Forest Products (NWFPs) are essential for the food and nutritional security of populations worldwide that rely on forests. Locals and indigenous communities, like the Tharu tribe in the Terai region of Uttar Pradesh, particularly in and around the Sohelwa Wildlife Sanctuary, rely heavily on edible and medicinal resources derived from forests for subsistence, seasonal nutrition, traditional healthcare, and livelihood support. Sohelwa Wildlife Sanctuary possesses rich floral diversity comprising wild fruits, leafy vegetables, tubers, mushrooms, medicinal plants, fodder resources, and other useful species. These resources make a significant contribution to household food systems, especially during agricultural lean periods and socio-economic crises. The present chapter examines the diversity, utilisation, and socio-economic significance of NWFPs in relation to food security in the Sohelwa Wildlife Sanctuary landscape. The chapter further discusses traditional ecological knowledge, nutritional contributions, gender dimensions, market potential, sustainability concerns, and conservation challenges associated with NWFP utilisation. Recommendations for sustainable management and policy integration are also highlighted.

## 1. Introduction

Throughout history, forests have provided food, medicine, shelter, fuel, and other necessities for human societies. In addition to timber, forests provide a wide range of biological products, which are referred to as Non-Wood Forest Products (NWFPs) or Non-Timber Forest Products (NTFPs). Non-Wood Forest Products (NWFPs) include fruits, seeds, nuts, leaves, tubers, mushrooms, medicinal plants, fibres, feed, gums, resins, honey, and other biological resources derived from forest environments (FAO, 1999).

Globally, approximately 1.6 billion people depend partially or wholly on forest resources for subsistence and livelihood support. In developing countries, NWFPs are particularly important for marginalised and indigenous communities where they function as safety nets during food shortages, crop failures, and economic stress (Vedeld et al., 2007). Studies indicate that wild edible plants contribute significantly to dietary diversity, micronutrient intake, and household food security in tropical and subtropical regions (Muir, 2021).

The Terai ecosystem of northern India forms one of the ecologically productive zones of the Himalayan foothills and supports rich biodiversity. The Sohelwa Wildlife Sanctuary, situated along the Indo–Nepal border in the districts of Shravasti, Balrampur, and Gonda in Uttar Pradesh, represents an important component of the Terai landscape. The sanctuary is characterized by moist deciduous forests, grasslands, marshes, wetlands, and riverine habitats that sustain diverse floral and faunal resources (Chanchani et al., 2014). Forest-fringe populations residing around the sanctuary, especially the Tharu tribe, possess extensive traditional ecological knowledge related to the collection, processing, preservation, and utilization of wild edible forest resources. Such dependence on NWFPs remains closely linked with food security, nutrition, healthcare, and cultural identity (Ojha & Bala, 2025).

This chapter explores the role of NWFPs in food security in the Sohelwa Wildlife Sanctuary region, emphasizing biodiversity richness, traditional practices, nutritional significance, and sustainable management strategies.

## 2. Study Area: Sohelwa Wildlife Sanctuary

### 2.1 Geographic Location

The Sohelwa Wildlife Sanctuary (also spelt Suhelwa or Soheldev Wildlife Sanctuary) is located in the Terai region of Uttar Pradesh along the Indo–Nepal border. The sanctuary extends across the districts of Shravasti, Balrampur, and Gonda and covers approximately 452 km². It stretches nearly 120 km in length and 6–8 km in width (Uttar Pradesh Forest Department, 2026).

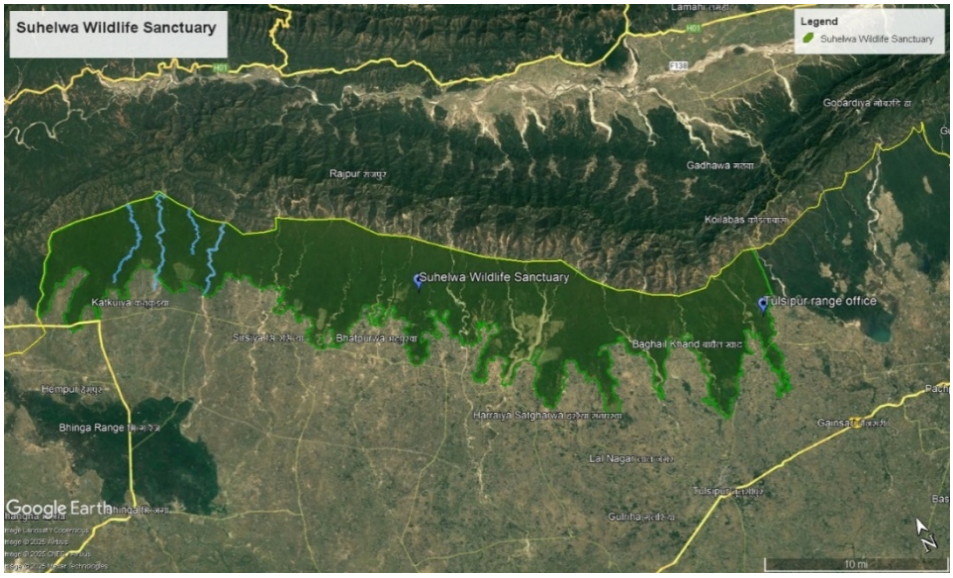



**Figure 1:** Sohelwa Wildlife Sanctuary (Source: Google Earth)

## 2.2 Climate and Vegetation

The climate of the region is humid subtropical with hot summers, heavy rainfall (during monsoon) and winters (from December to February).

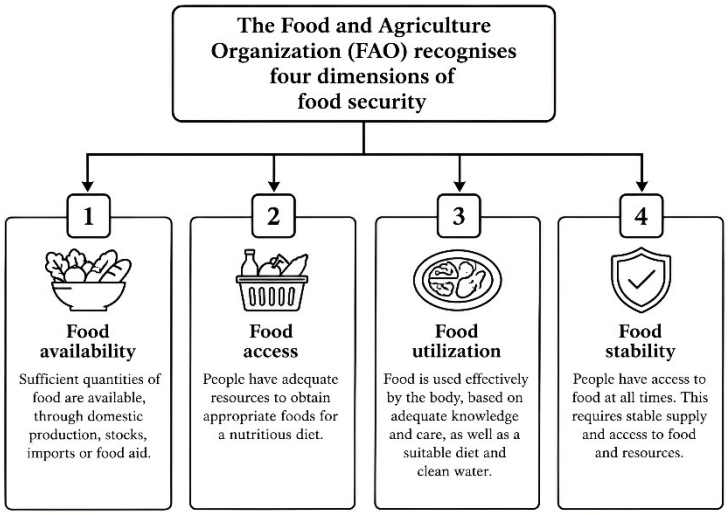


**Figure 2: a)** Forest canopy near Bhagwanpur **b)** Bhagwanpur wetland **(Source: Author)**

The SWLS supports Tropical moist deciduous forests, Sal (*Shorea robusta*) dominated forests, Grasslands, Wetlands and marshes, and Riverine vegetation. Dominant tree species include *Shorea robusta*, *Syzygium cumini*, *Terminalia bellirica, Acacia catechu*, *Bambusa* spp., *Mallotus philippensis* and *Madhuca longifolia*. The region forms part of the Terai-Bhabar ecological system, known for high biodiversity richness (UPEcotourism, 2026).

## 3. Concept of Food Security and NWFPs

Food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food necessary for an active and healthy life.




NWFPs contribute directly and indirectly to all these dimensions by providing edible products, enhancing dietary diversity, supporting income generation,acting as famine foods during crises and by supplying medicinal resources for nutritional health. In forest-dependent regions, NWFPs often bridge seasonal food gaps between agricultural harvests (Shackleton & Gumbo, 2010).

## 4. Diversity of NWFPs Based Food in Sohelwa Wildlife Sanctuary

The forests of Sohelwa Wildlife Sanctuary (SWLS) harbour a wide diversity of edible plant resources used traditionally by local communities.

**4.1 Wild Edible Fruits:** Wild fruits constitute one of the major categories of edible NWFPs in the region. These fruits are consumed fresh, dried, fermented, or processed into beverages and traditional foods.

**Common Wild Edible Fruits**

| Sr. No | Local Name | Botanical Name | Family | Edible Part |
|---|---|---|---|---|
| **1.** | Bael | *Aegle marmelos* L. | Rutaceae | Fruit pulp |
| **2.** | Jamun | *Syzygium cumini* | Myrtaceae | Fruits |
| **3.** | Ber | *Ziziphus mauritiana* | Rhamnaceae | Fruits |
| **4.** | Tamarind | *Tamarindus indica* | Fabaceae | Fruit pulp |
| **5.** | Mahua | *Madhuca longifolia* | Sapotaceae | Flowers & fruits |
| **6.** | Gular | *Ficus racemosa* | Moraceae | Fruits |
| **7.** | Kathal | *Artocarpus heterophyllus* | Moraceae | Fruits & seeds |
| **8.** | Barhal | *Artocarpus lakoocha* Roxb.; | Moraceae | Fruit |
| **9.** | Karonda | *Carissa carandas* L. | Apocyanaceae | Fruit |
| **10.** | Jungali Kundru; | *Coccinia grandis* (L.) Voigt. | Cucurbitaceae | Fruit |
| **11.** | Tendu | *Diospyros chloroxylon* Roxb. | Ebenaceae | Fruit |
| **12.** | Mahua | *Madhuca longifolia var. latifolia* (Roxb.) A. Chev. | Sapotaceae | Flowers & fruits |
| **13.** | Sahjan | *Moringa oleifera* Lamk. | Moringaceae | Fruit |
| **14.** | Shahtoot | *Morus indica* L. | Moraceae | Fruit |

Naturally growing fruits are high in calcium, iron, vitamin C, antioxidants, and dietary fibre. In low agricultural seasons, these resources are particularly crucial. (Fentahun and Hager 2009).



**A.** *Morus indica* L.



**B.** *Phyllanthus emblica* L.

| | |
|---|---|
|  |  |
| **C.** *Atrocarpus heterophyllus* | **D.** *Aegle marmelos* L. |
|  |  |
| **E.** *Carissa carandas* L. | **F.** *Pithecellobium dulce* (Roxb.) Benth. |

| | |
|---|---|
|  |  |
| **G.** *Annona squamosa* L. | **H.** *Ziziphus mauritiana* |
|  |  |
| **I.** *Coccinia grandis* (L.) Voigt. | **J.** *Cucumis melo* L. |

**Figure 3** (A-J)**:** Major Wild Edible NWFP Species of Sohelwa Landscape. (**Source: Author)**

### 4.2 Wild Leafy Vegetables

Green leafy vegetables from forests offer vitamins that are vital for rural nutrition and are traditionally eaten as seasonal foods. (Powell et al., 2013).Important leafy vegetables include *Amaranthus viridis*, *Centella asiatica*, *Moringa oleifera*, *Chenopodium album*, and *Colocasia esculenta*. These leafy vegetables contribute significantly to iron intake, Vitamin A supplementation and mineral nutrition (Sarkar et al., 2023).



**Figure:** 4) *Amaranthus viridis:* A leafy vegetable

### 4.3 Tubers and Corms as Underground Food Resources

Tubers and cormsof wild-growing *Dioscorea bulbifera* (tuber), *Dioscorea alata* (tuber), *Colocasia esculenta* (corm) in the SWLS are edible. The food in such plants is stored in the underground stem in the form of Tubers, Corm (Harvey 2007). These plant organs are formed as organs of perennation and germinate to give rise to a new plant in the wild when favourable environmental conditions return. These are rich sources of carbohydrates and minerals, and when consumed, they fulfil the body's energy requirements

### 4.4 Mushrooms and Fungi

Mushrooms like *Astraeus hygrometricus (*Pers.) Morgan (Diplocystaceae) grows well in SWLS during the rainy season.



**Figure 5:** *Astraeus hygrometricus (*Pers.)

It is highly valued as a wild edible mushroom and is collected, consumed and sold during the monsoon, contributing to protein supplementation among forest-fringe communities. Traditional knowledge helps them to distinguish edible and poisonous species (Verma, R. K., et al. 2019).

### 4.5 Flowers and Seeds

Flowers of *Madhuca longifolia* (Mahua) are highly significant, as they are used as food, livestock feed, in traditional sweets, and fermented into beverages. Mahua flowers contain a considerable amount of carbohydrates and are economically important in rural economies. Oil extracted from the seeds are used as edible oil. In our research we found that seeds of *Artocarpus heterophyllus* Lamk. (Moraceae) is eaten, boiled/roasted or cooked as vegetable by the local residence of SWLS.





**Figure: 6** A) Seeds of *Madhuca longifolia* B) Fruit of *Atrocarpus heterophyllous*

## 5. Role of NWFPs in Household Food Security

**5.1 Seasonal Food Buffer:** NWFPs function as seasonal food reserves during, Crop failures, Floods, Droughts and Agricultural lean periods. Forest products collected during summer and monsoon often compensate for food shortages.

**5.2 Nutritional Security:** NWFP species are source of essential nutrients often lacking in staple cereal-based diets. Wild species are good source of Vitamins, Minerals, Proteins Phytochemicals and Antioxidants which ensure Nutritional Benefits (Kabwe et al. 2024). Studies from Himalayan and Terai ecosystems demonstrate that wild edible plants improve dietary diversity and nutritional resilience (Rafeeq et al. 2025)

**5.3 Income Generation and Food Access:** Economically important NWFPs such as mahua flowers, honey, medicinal plants, bamboo products, and wild fruits are sold in local markets, allowing households to purchase staple foods and essential commodities. The supplementary income improves food purchasing capacity among economically marginalised households (Shackleton et al. 2024).

## 6. Indigenous Knowledge and Food Traditions

The Tharu community possesses extensive traditional ecological knowledge related to Edible plant identification, harvesting seasons, preservation techniques, processing methods, and ethnomedicinal uses.





| | |
|---|---|
| **Figure:** 7A) Ethnomedicinal data collection from the Tharu community | B) Interaction with Tharu tribe for collecting information on Collection and use of NWFP |

Traditional food systems involve sun-drying of fruits, fermentation, pickling, and preparation of herbal foods. This indigenous knowledge contributes significantly to sustainable resource use and biodiversity conservation. (Thorn et al., 2020). In the study, we found that the Tharu community people and local villagers of SWLS collect wild fruits of *Carissa carandus* (karaunda) and prepare pickles for use throughout the year. Flowers of *Madhuca longifolia* (Mahua) are dried for later use and sale. Research work by Madhvi Awasthi (2011) shows that the flower buds of *Bauhinia variegata* (Kachnar) and *Bombax ceiba* (Semal) are used to prepare Biriya and Pakora, and are dried for later use to prepare curries and other dishes.

**7. Gender Dimensions in NWFP Collection**

In our study, during the survey, we found that elderly men and women play central roles in the collection of edible forest products, processing and preservation, household nutrition management, and marketing of surplus products. According to Tata Ngome (2017), Women and older men have detailed knowledge of the nutritional properties, medicinal uses, and seasonal availability of species. Thus, NWFP management and food security are closely linked with the traditional knowledge system of elderly people.

**8. Biodiversity Conservation and Sustainable Harvesting**

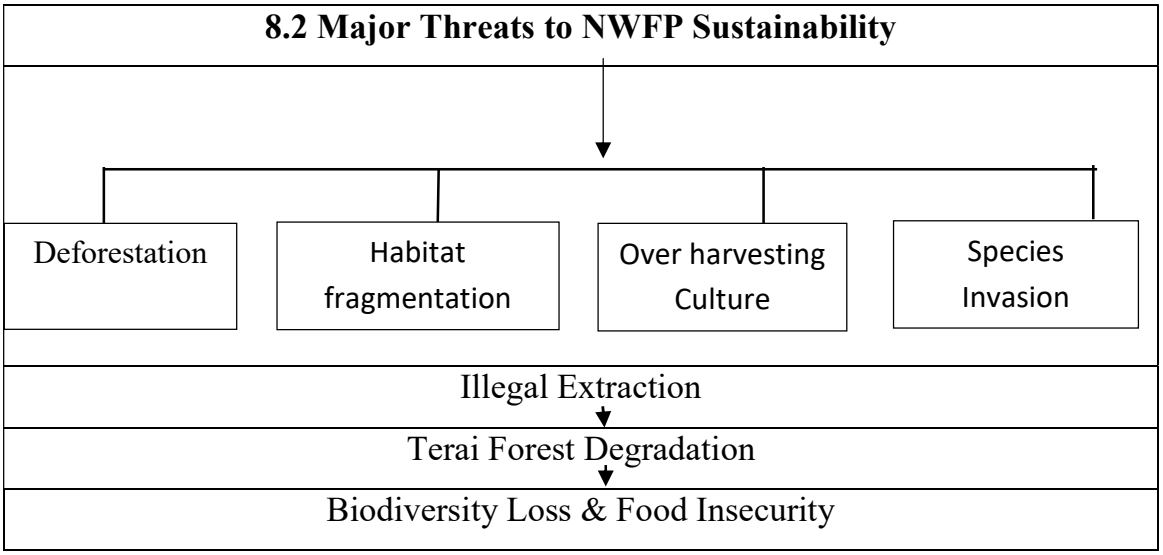
The sustainability of food-based NWFPs depends upon healthy forest ecosystems.

**8. 1 Ecological Importance**

NWFP-based livelihoods encourage forest conservation, species protection, traditional agroforestry systems, and habitat preservation.

**8.2 Threats to Sustainability**

Major threats include deforestation, habitat fragmentation, overharvesting, agricultural expansion, species invasionand illegal extraction. The degradation of Terai forests threatens both biodiversity and food security.




## 9. Challenges Associated with NWFP-Based Food Security

**9.1 Declining Forest Cover:** Rapid developmental activities, urban expansion, infrastructure growth, and increasing anthropogenic pressures have resulted in a continuous decline in forest cover, thereby posing serious threats to biodiversity, ecological stability, and the livelihood security of forest-dependent communities (Hughes, 2017).

**9.2 Market Exploitation:** The people who are directly involved in the collection of non - wood forest products get very low economic return due to lack of storage facilities, middleman exploitation and poor market accessibility (Pandey et al., 2016).

**9.3 Erosion of Traditional Knowledge:** Modernisation and changing lifestyles reduce the transmission of indigenous knowledge from generation to generation.

**9.4 Climate Change:** Climate change affects fruiting cycles, species distribution, and forest production; these changes are not only abrupt but also the result of human activity, including deforestation, industrialisation, the use of agrochemicals, and many other factors (Azhar et al., 2021).

**10. Sustainable Management Strategies:** Sustainable management strategies include

- Local community participation in conservation and harvesting decisions will improve sustainability.

- Ethnobotanical documentation is essential for preserving indigenous food systems.
- Processing of NWFPs into pickles, beverages, dried products, and herbal foods can increase household income.
- Government initiatives should strengthen forest rights, promote local enterprises, support women's cooperatives and encourage sustainable harvesting.
- Awareness programs among the local people can promote sustainable utilisation and biodiversity conservation.

## 11. Conclusion

Non-Wood Forest Products are an important component of food security and livelihood resilience in the Sohelwa Wildlife Sanctuary landscape. The Terai forests are rich in biodiversity and host many species that are edible, medicinal and economically important to local and indigenous communities, especially the Tharu tribe.NWFPs are crucial for nutritional security, diet diversity, seasonal food buffering, traditional healthcare and household income generation. However, increasing human pressure, habitat degradation, unsustainable harvesting and socio-economic transitions pose threats to biodiversity and traditional food systems.

The Sohelwa region needs sustainable management approaches that include community participation, indigenous knowledge, biodiversity conservation, scientific management and market support to maintain ecological sustainability and food security.Future research needs to focus on nutritional profiling of wild edible species, climate resilience of NWFP resources, community-based conservation models, sustainable value chains and ethnobotanical documentation.

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# Nature-Based Solutions (NbS) for Biodiversity Conservation: Principles, Applications, Challenges, and Future Perspectives

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***Abstract***

Biodiversity loss, driven by habitat degradation, climate change, pollution, invasive species, and unsustainable resource use, poses a major global environmental challenge. Nature-Based Solutions (NbS) have emerged as an effective approach to address these interconnected issues by protecting, sustainably managing, and restoring ecosystems while enhancing biodiversity and human well-being. According to the International Union for Conservation of Nature (IUCN), NbS utilize natural processes to tackle societal challenges and deliver multiple ecosystem services, including carbon sequestration, water purification, flood regulation, and habitat restoration. The core principles of NbS emphasize ecosystem integrity, stakeholder participation, adaptive management, and long-term sustainability. Key applications include forest and wetland restoration, mangrove conservation, agroforestry, urban green infrastructure, and river rehabilitation, which contribute to biodiversity conservation, climate resilience, food security, and sustainable livelihoods. However, widespread implementation is constrained by financial limitations, governance challenges, land-use conflicts, and inadequate monitoring. Emerging technologies such as Artificial Intelligence (AI), Geographic Information Systems (GIS), remote sensing, drones, and environmental DNA (eDNA) are enhancing the planning and assessment of NbS initiatives. Integrating NbS into environmental policies and climate adaptation strategies, supported by scientific research and international collaboration, will be essential for achieving global biodiversity and sustainable development targets.

***Keywords*****:** Nature-Based Solutions, Biodiversity Conservation, Ecosystem Restoration, Climate Change, Ecosystem Services, Sustainable Development, Wetlands, Forest Restoration, Environmental Management.

**Introduction**:

Biodiversity forms the foundation of life on Earth by supporting ecosystem functioning, maintaining ecological balance, and providing essential ecosystem services that sustain human well-being. It encompasses the diversity of genes, species, and ecosystems, which collectively regulate nutrient cycling, pollination, climate regulation, water purification, carbon sequestration, and food production. However, biodiversity is declining at an unprecedented rate due to anthropogenic pressures such as habitat destruction, deforestation, pollution, overexploitation of natural resources, invasive alien species, and climate change. The degradation of natural ecosystems

threatens ecological stability, food and water security, public health, and global economic development. Consequently, biodiversity conservation has become one of the foremost environmental priorities of the twenty-first century (IPBES, 2019; CBD, 2022).

Conventional conservation approaches have traditionally focused on establishing protected areas, species recovery programmes, and legislative measures to reduce environmental degradation. Although these strategies have contributed significantly to conserving threatened species and habitats, they are often insufficient to address the complex interactions among biodiversity loss, climate change, ecosystem degradation, and increasing human demands on natural resources. Growing recognition of these interconnected challenges has stimulated the development of more integrated and adaptive conservation approaches that simultaneously benefit both ecosystems and society. Among these, **Nature-Based Solutions (NbS)** have emerged as a transformative framework for achieving sustainable development while conserving biodiversity (Cohen-Shacham*et al*., 2019).

The International Union for Conservation of Nature (IUCN) defines Nature-Based Solutions as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2020). Similarly, the United Nations Environment Programme (UNEP) describes NbS as actions that conserve, restore, and sustainably manage terrestrial, freshwater, coastal, and marine ecosystems while delivering environmental, social, and economic benefits (UNEP, 2024). Unlike conventional engineering solutions, NbS harness natural ecological processes to enhance ecosystem resilience, reduce disaster risks, improve climate adaptation, strengthen food and water security, and promote sustainable livelihoods while maintaining ecosystem integrity.

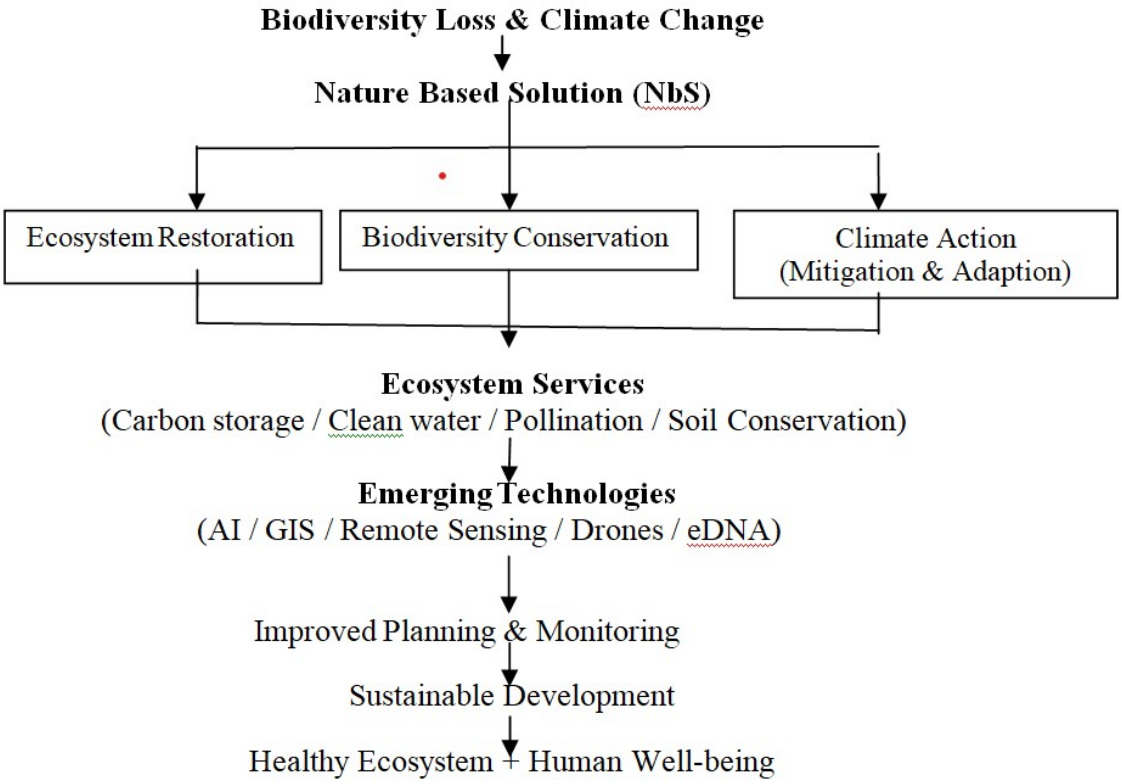
Nature-Based Solutions represent a paradigm shift from viewing biodiversity conservation as an isolated environmental objective to recognizing biodiversity as the foundation for addressing multiple societal challenges. Healthy ecosystems not only conserve species diversity but also provide essential ecosystem services such as carbon storage, flood regulation, groundwater recharge, erosion control, nutrient cycling, and disease regulation. Restoration of forests, wetlands, mangroves, grasslands, peatlands, coral reefs, and river ecosystems has demonstrated considerable potential to simultaneously mitigate climate change, reduce disaster vulnerability, improve water quality, and conserve biodiversity. Consequently, NbS are increasingly recognized as cost-effective and multifunctional alternatives or complements to conventional grey infrastructure (Cohen-Shacham*et al*., 2019; IUCN, 2020).

Recent international environmental agreements have further strengthened the importance of Nature-Based Solutions in global conservation strategies. The **Kunming–Montreal Global Biodiversity Framework (KMGBF)**, adopted under

the Convention on Biological Diversity in 2022, emphasizes ecosystem restoration, conservation of at least 30% of terrestrial and marine areas by 2030, sustainable management of natural resources, and integration of biodiversity into national development planning. Nature-Based Solutions are regarded as one of the principal mechanisms for achieving these ambitious global biodiversity targets while simultaneously contributing to the Sustainable Development Goals (SDGs), the Paris Agreement on Climate Change, and the United Nations Decade on Ecosystem Restoration (2021–2030).

The application of NbS spans diverse ecological and socio-economic contexts. Forest landscape restoration enhances habitat connectivity and carbon sequestration; wetland restoration improves water quality and supports freshwater biodiversity; mangrove conservation protects coastal communities from storm surges while serving as critical nurseries for marine organisms; agroforestry systems enhance agricultural productivity while conserving biodiversity; and urban green infrastructure improves environmental quality, reduces urban heat islands, and supports pollinators and urban wildlife. In freshwater ecosystems, restoration of rivers, floodplains, and wetlands is increasingly recognized as an effective strategy for conserving aquatic biodiversity, maintaining ecological flows, and improving fisheries productivity.

Despite their considerable potential, successful implementation of Nature-Based Solutions faces several scientific, financial, institutional, and governance challenges. Limited funding, inadequate monitoring frameworks, land-use conflicts, policy fragmentation, insufficient stakeholder participation, and uncertainties associated with climate change often constrain the long-term effectiveness of NbS initiatives. Furthermore, poorly designed restoration projects that prioritize carbon sequestration without considering native biodiversity may produce unintended ecological consequences. Therefore, the IUCN Global Standard for Nature-Based Solutions emphasizes eight guiding criteria, including adaptive management, biodiversity integrity, stakeholder participation, economic viability, and equitable governance, to ensure high-quality implementation and measurable conservation outcomes.




Rapid advances in science and technology are further enhancing the effectiveness of NbS. Artificial Intelligence (AI), Geographic Information Systems (GIS), remote sensing, drone technology, environmental DNA (eDNA), Internet of Things (IoT) sensors, and big-data analytics enable more accurate ecosystem monitoring, habitat mapping, biodiversity assessment, and adaptive management. These technologies facilitate evidence-based decision-making and improve the evaluation of restoration success across landscapes and ecosystems. Recent reviews indicate that integrating digital technologies with ecosystem-based management can significantly improve the planning, implementation, and long-term monitoring of Nature-Based Solutions while supporting adaptive conservation strategies.

Given the accelerating biodiversity crisis and the urgent need for sustainable environmental management, Nature-Based Solutions have emerged as an essential framework for reconciling ecological conservation with socio-economic development. This chapter examines the fundamental principles of NbS, explores their diverse applications in biodiversity conservation, discusses the major ecological and governance challenges associated with their implementation, and highlights future research directions and technological innovations that can enhance their effectiveness in achieving resilient ecosystems and sustainable development.

***Concept and Evolution of Nature-Based Solutions:***

Nature-Based Solutions (NbS) refer to actions that protect, sustainably manage, restore, and enhance natural or modified ecosystems to address societal challenges

while simultaneously providing benefits for biodiversity, ecosystem services, and human well-being. The concept emphasizes working with nature rather than relying solely on conventional engineering approaches to tackle issues such as climate change, biodiversity loss, water scarcity, disaster risk, and food security (IUCN, 2020). By integrating ecological principles into development planning, NbS contribute to environmental sustainability, economic resilience, and social inclusion.

The foundation of Nature-Based Solutions lies in earlier concepts such as ecosystem management, ecological restoration, ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction (Eco-DRR), and green infrastructure. These approaches highlighted the importance of maintaining healthy ecosystems to provide essential ecosystem services, including carbon sequestration, water purification, flood regulation, soil conservation, and habitat protection (Millennium Ecosystem Assessment, 2005). Over time, these concepts converged into the broader NbS framework, which recognizes the interconnectedness of ecological health and human development.

The term "Nature-Based Solutions" gained international prominence in the late 2000s through the International Union for Conservation of Nature (IUCN), which promoted NbS as an integrated approach to simultaneously address environmental, social, and economic challenges (IUCN, 2020). Subsequently, the European Commission adopted the concept and expanded its application to urban development, climate adaptation, biodiversity conservation, and sustainable economic growth. According to the European Commission (2021), NbS are inspired and supported by nature, are cost-effective, and deliver environmental, social, and economic benefits while enhancing ecosystem resilience.

The evolution of NbS has been closely linked to major international environmental agreements. The adoption of the Paris Agreement in 2015 recognized the critical role of forests, wetlands, and other ecosystems in mitigating greenhouse gas emissions and enhancing climate adaptation (United Nations Framework Convention on Climate Change [UNFCCC], 2015). Similarly, the United Nations Sustainable Development Goals (SDGs), particularly Goals 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land), emphasize ecosystem conservation and restoration as essential components of sustainable development (United Nations, 2015). More recently, the Kunming-Montreal Global Biodiversity Framework has reinforced the importance of ecosystem restoration and biodiversity conservation through nature-based approaches.

Nature-Based Solutions encompass a broad range of interventions across different sectors. In urban environments, green roofs, urban forests, permeable pavements, wetlands, and rain gardens reduce urban heat, improve air quality, and manage stormwater. In agriculture, agroforestry, conservation agriculture, and

regenerative farming improve soil fertility, enhance biodiversity, and increase climate resilience. Coastal NbS, including mangrove restoration, coral reef conservation, and salt marsh protection, reduce coastal erosion, buffer storm surges, and store significant amounts of carbon. Similarly, restoring forests and river ecosystems contributes to flood mitigation, water security, and biodiversity conservation (Cohen-Shacham et al., 2016).

A defining characteristic of NbS is their ability to generate multiple co-benefits. Unlike traditional grey infrastructure, which is often designed for a single purpose, NbS provide integrated outcomes such as climate change mitigation, disaster risk reduction, biodiversity enhancement, improved public health, and livelihood opportunities. Furthermore, NbS are generally more adaptable and cost-effective over the long term because they strengthen natural ecosystem functions rather than replacing them with artificial systems (European Commission, 2021).

Despite their growing acceptance, the implementation of Nature-Based Solutions faces several challenges, including limited financial investment, fragmented governance, land-use conflicts, inadequate technical capacity, and difficulties in monitoring ecosystem outcomes. Addressing these barriers requires interdisciplinary collaboration, supportive public policies, stakeholder participation, and long-term investment in ecosystem conservation and restoration. As climate change and environmental degradation continue to intensify, Nature-Based Solutions have evolved into a globally recognized framework for achieving climate resilience, biodiversity conservation, and sustainable development. Their integration into environmental policy and planning demonstrates a significant shift toward development pathways that value nature as a critical partner in addressing complex global challenges.

**Principles of Nature-based Solutions:**

The International Union for Conservation of Nature (IUCN) developed the principles of Nature-based Solutions (NbS) to guide conservation actions that benefit both biodiversity and human well-being. NbS emphasize protecting, restoring, and sustainably managing ecosystems while addressing climate change, water and food security, and disaster risk reduction. Key principles include: (i) conserving and restoring nature as the foundation of all interventions; (ii) integrating NbS with technological and engineering solutions where appropriate; (iii) designing site-specific strategies based on ecological, social, and cultural contexts; (iv) ensuring equitable governance and stakeholder participation; (v) maintaining biodiversity and ecosystem integrity; (vi) adopting a landscape or seascape approach to enhance ecological connectivity; (vii) recognizing and managing trade-offs between conservation and development goals; and (viii) integrating NbS into policies, biodiversity strategies, climate adaptation plans, and sustainable development frameworks to ensure long-term environmental and societal benefits.

**Biodiversity Crisis: Why Nature-Based Solutions are Needed:**

Biodiversity is declining rapidly because of habitat destruction, climate change, pollution, overuse of natural resources, and the spread of invasive species. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), nearly one million plant and animal species are at risk of extinction unless urgent conservation actions are taken (IPBES, 2019). The loss of biodiversity reduces the ability of ecosystems to function properly and affects important ecosystem services such as pollination, clean water, carbon storage, and soil fertility. As a result, food security, human health, livelihoods, and overall environmental stability are threatened. Traditional conservation methods alone are often not enough to solve these complex environmental problems. Nature-Based Solutions (NbS) provide a sustainable approach by protecting, restoring, and managing ecosystems while also meeting human needs. They help restore forests, wetlands, and other natural habitats, improve ecosystem connectivity, increase resilience to climate change, conserve biodiversity, and support sustainable livelihoods. By integrating ecological restoration with community participation and sustainable development, NbS support global biodiversity conservation goals, including the Kunming–Montreal Global Biodiversity Framework, the Sustainable Development Goals (SDGs), and climate action. Therefore, NbS are increasingly recognized as an effective way to conserve biodiversity while improving human well-being.

**Major Types of Nature-Based Solutions:**

Nature-Based Solutions (NbS) include a wide range of ecosystem-based approaches that restore, protect, and sustainably manage natural resources while addressing environmental and societal challenges. **Forest restoration** improves biodiversity, enhances carbon sequestration, prevents soil erosion, and regulates the water cycle. **Wetland restoration** revives degraded wetlands, improving water quality, flood control, groundwater recharge, and habitats for diverse flora and fauna. **Mangrove restoration** protects coastal areas from erosion and storm surges, supports fisheries, and stores large amounts of blue carbon. **River restoration** focuses on restoring natural river channels, reconnecting floodplains, improving water quality, and conserving freshwater biodiversity. **Agroforestry**, which integrates trees with crops and livestock, enhances soil fertility, increases farm productivity, conserves biodiversity, and strengthens climate resilience. **Urban green infrastructure**, including parks, green roofs, urban forests, and rain gardens, reduces urban heat islands, improves air quality, manages stormwater, and enhances human well-being. **Coastal ecosystem restoration**, including coral reefs, seagrass meadows, salt marshes, and dunes, protects shorelines, conserves marine biodiversity, supports fisheries, and increases resilience to climate change and sea-level rise. Collectively, these Nature-Based Solutions strengthen ecosystem health, improve biodiversity

conservation, enhance ecosystem services, and support sustainable development while providing long-term environmental, economic, and social benefits.

**Nature-Based Solutions (NbS) for Biodiversity Conservation:**

Nature-Based Solutions (NbS) are an effective way to conserve biodiversity by protecting, restoring, and sustainably managing natural ecosystems while also addressing environmental and social challenges. Unlike traditional conservation methods that mainly focus on protecting specific areas, NbS take a broader ecosystem approach that improves the health and resilience of entire landscapes. Activities such as forest restoration, wetland rehabilitation, mangrove plantation, and river restoration create suitable habitats for plants and animals, reconnect fragmented ecosystems, and support the recovery of threatened and endangered species while maintaining genetic diversity.

NbS also improve important ecosystem services, including pollination, nutrient cycling, soil conservation, water purification, and carbon storage. Sustainable land-use practices such as agroforestry, community forestry, and watershed management help reduce pressure on natural resources while providing income and livelihood opportunities for local communities. In coastal and marine regions, restoring mangroves, coral reefs, seagrass meadows, and salt marshes protects biodiversity, provides breeding grounds for fish, reduces coastal erosion, and increases resilience to climate change. NbS also promote the active participation of indigenous peoples and local communities, whose traditional knowledge helps in the sustainable management of ecosystems. By combining biodiversity conservation with climate action, disaster risk reduction, and sustainable development, NbS support global initiatives such as the Kunming–Montreal Global Biodiversity Framework, the Sustainable Development Goals (SDGs), and the Paris Agreement. Therefore, NbS are widely recognized as a practical, sustainable, and cost-effective approach for conserving biodiversity and improving ecosystem and human well-being.

**Nature-Based Solutions (NbS) and Climate Change Mitigation & Adaptation:**

Nature-Based Solutions (NbS) are increasingly recognized as an effective approach for addressing climate change while conserving biodiversity and supporting sustainable development. They help mitigate climate change by protecting, restoring, and sustainably managing ecosystems that absorb and store large amounts of carbon dioxide. Forests, wetlands, mangroves, peatlands, grasslands, and seagrass meadows act as important carbon sinks, reducing greenhouse gas concentrations in the atmosphere. Reforestation, afforestation, wetland restoration, and sustainable land management therefore contribute significantly to climate change mitigation (Griscom*et al*., 2017).

NbS also strengthen climate change adaptation by improving the resilience of ecosystems and communities to climate-related hazards. Restored forests reduce soil erosion and landslides, while healthy wetlands absorb excess rainfall, reduce flooding,

and recharge groundwater. Mangroves, coral reefs, and coastal wetlands protect shorelines from storm surges, cyclones, and sea-level rise. Agroforestry enhances soil fertility, conserves water, and increases crop productivity, helping farmers adapt to changing climatic conditions. Similarly, urban green infrastructure such as parks, green roofs, and urban forests lowers temperatures, reduces the urban heat island effect, improves air quality, and manages stormwater.

In addition to environmental benefits, NbS provide economic and social advantages by supporting livelihoods, improving food and water security, and reducing disaster risks. They also contribute to international commitments, including the Paris Agreement, the Kunming–Montreal Global Biodiversity Framework, and the Sustainable Development Goals (SDGs). By combining climate action with biodiversity conservation and human well-being, Nature-Based Solutions offer a sustainable, cost-effective, and long-term strategy for building climate-resilient ecosystems and communities.

**Ecosystem Services Delivered by Nature-Based Solutions (NbS):**

Nature-Based Solutions (NbS) provide many valuable ecosystem services that support both nature and human well-being. By protecting, restoring, and sustainably managing ecosystems, NbS help maintain the natural processes that are essential for life. Healthy forests, wetlands, rivers, grasslands, mangroves, and coastal ecosystems provide a wide range of ecological, economic, and social benefits (Costanza, *et al.*1997).

One of the most important ecosystem services of NbS is **climate regulation**. Forests, wetlands, and mangroves absorb and store carbon dioxide, helping to reduce global warming. NbS also improve **water resources** by filtering pollutants, recharging groundwater, reducing floods, and maintaining river flow during dry seasons. Healthy ecosystems protect the soil by reducing erosion, improving soil fertility, and supporting nutrient cycling, which increases agricultural productivity.

NbS also support **biodiversity conservation** by providing food, shelter, and breeding habitats for plants, animals, birds, fish, and pollinating insects. These ecosystems maintain ecological balance and improve ecosystem resilience against environmental disturbances. In coastal areas, mangroves, coral reefs, and salt marshes protect shorelines from storms, cyclones, and sea-level rise.

Besides environmental benefits, NbS provide important **social and economic services**. They support sustainable agriculture, fisheries, forestry, and ecotourism, creating employment and improving local livelihoods. Urban green spaces such as parks and green roofs improve air quality, reduce heat, promote recreation, and enhance physical and mental health. Overall, Nature-Based Solutions deliver multiple ecosystem services that improve environmental quality, strengthen climate resilience, conserve biodiversity, and support sustainable development for present and future generations.

**Emerging Technologies Supporting Nature-Based Solutions (NbS):**

Emerging technologies are making Nature-Based Solutions (NbS) more effective by improving ecosystem monitoring, conservation planning, and restoration. These technologies help scientists, policymakers, and conservationists collect accurate data, monitor environmental changes, and make better decisions for biodiversity conservation (Bush*et al*., 2017).

**Artificial Intelligence (AI)** is widely used to analyze large amounts of environmental data. AI can identify plant and animal species from camera trap images and sounds, predict biodiversity changes, detect illegal logging and poaching, and monitor ecosystem health. AI also helps in planning habitat restoration and assessing the impacts of climate change.

**Remote sensing** uses satellite images and aerial photographs to monitor forests, wetlands, rivers, and coastal ecosystems over large areas. It helps detect deforestation, land-use changes, forest fires, droughts, floods, and habitat degradation in real time.

**Geographic Information System (GIS)** is an important tool for mapping and analyzing environmental data. GIS helps identify biodiversity hotspots, monitor habitat fragmentation, plan protected areas, and prioritize ecosystem restoration projects. It also supports decision-making by combining spatial, ecological, and socio-economic information (Tabak et al., 2019).

**Drones (Unmanned Aerial Vehicles)** provide high-resolution images of forests, wetlands, rivers, and coastal regions. They are useful for wildlife surveys, vegetation mapping, monitoring restoration projects, and detecting illegal activities in remote areas. Drones are faster, safer, and more cost-effective than traditional field surveys (Thomsen et al., 2015).

**Environmental DNA (eDNA)** is a modern technique that detects DNA released by organisms into water, soil, or air. It allows scientists to identify species without capturing or disturbing them. eDNA is especially useful for monitoring rare, endangered, invasive, and aquatic species and assessing biodiversity in rivers, lakes, and wetlands.

Together, these technologies improve the planning, implementation, and monitoring of Nature-Based Solutions. They provide accurate information, reduce monitoring costs, support biodiversity conservation, and help build resilient ecosystems capable of adapting to climate change

**Challenges and Limitations of NbS for Biodiversity Conservation:**

Nature-Based Solutions (NbS) offer an effective approach to biodiversity conservation, but several challenges limit their successful implementation. One of the main challenges is the **lack of adequate funding** for ecosystem restoration, conservation, and long-term monitoring. Many biodiversity-rich regions, especially in

developing countries, have limited financial and technical resources to implement NbS effectively (Seddon et al., 2022).

Another major limitation is **habitat loss and land-use change** caused by urbanization, agriculture, mining, and infrastructure development. These activities reduce natural habitats and make ecosystem restoration more difficult. **Climate change** further threatens biodiversity by increasing temperatures, altering rainfall patterns, causing droughts, floods, wildfires, and sea-level rise, which can reduce the success of restoration efforts (UNEP, 2022).

**Weak governance, poor policy implementation, and lack of coordination** among government agencies, local communities, and conservation organizations also affect the effectiveness of NbS. In many cases, conflicts over land ownership and resource use delay or prevent restoration projects. In addition, **limited scientific data, biodiversity monitoring, and ecological research** make it difficult to evaluate the long-term success of NbS.

Another challenge is the **invasion of non-native species**, pollution, and overexploitation of natural resources, which continue to degrade ecosystems even after restoration. Some restoration projects may also focus on planting a few fast-growing tree species instead of restoring diverse native ecosystems, resulting in lower biodiversity benefits.

Finally, successful NbS require **active participation of local communities, indigenous peoples, policymakers, and scientists**. Without awareness, capacity building, and long-term management, many projects fail to achieve their conservation goals. Despite these challenges, improved policies, adequate funding, scientific monitoring, community participation, and the use of modern technologies such as GIS, remote sensing, AI, and environmental DNA (eDNA) can significantly enhance the effectiveness of Nature-Based Solutions for biodiversity conservation.

## *Conclusion:*

Nature-Based Solutions (NbS) have emerged as an effective and sustainable approach for conserving biodiversity while addressing major environmental and societal challenges. The rapid loss of biodiversity, ecosystem degradation, climate change, pollution, and unsustainable use of natural resources threaten ecosystem stability and human well-being. Unlike conventional conservation methods that mainly focus on protecting individual species or habitats, NbS provide an integrated ecosystem-based approach that simultaneously supports biodiversity conservation, climate change mitigation and adaptation, disaster risk reduction, water security, food security, and sustainable livelihoods.

This chapter highlights the fundamental principles of NbS developed by the International Union for Conservation of Nature (IUCN), emphasizing ecosystem restoration, biodiversity conservation, stakeholder participation, adaptive management, and sustainable governance. Various NbS approaches, including forest

restoration, wetland restoration, mangrove conservation, river restoration, agroforestry, urban green infrastructure, and coastal ecosystem restoration, play an important role in improving ecosystem health and resilience while providing multiple ecosystem services such as carbon sequestration, water purification, soil conservation, pollination, and flood regulation.

The integration of emerging technologies such as Artificial Intelligence (AI), Geographic Information Systems (GIS), remote sensing, drones, and environmental DNA (eDNA) has significantly improved the planning, implementation, monitoring, and evaluation of NbS. These technologies enable accurate biodiversity assessment, habitat mapping, ecosystem monitoring, and evidence-based decision-making, thereby increasing the effectiveness of restoration programmes.

Despite their considerable benefits, the successful implementation of NbS continues to face challenges, including inadequate funding, weak governance, land-use conflicts, climate change, invasive species, limited scientific monitoring, and insufficient public participation. Addressing these challenges requires stronger environmental policies, long-term financial investment, interdisciplinary research, active involvement of local communities and indigenous peoples, and international cooperation. Continuous monitoring and adaptive management are also essential to ensure the long-term success of NbS projects.

As global environmental challenges continue to intensify, Nature-Based Solutions offer a practical, cost-effective, and sustainable pathway for balancing biodiversity conservation with socio-economic development. Integrating NbS into national biodiversity strategies, climate adaptation plans, and sustainable development policies will be essential for achieving the goals of the Kunming–Montreal Global Biodiversity Framework, the Paris Agreement, the Sustainable Development Goals (SDGs), and the United Nations Decade on Ecosystem Restoration. Investing in nature today will not only conserve biodiversity but also strengthen ecosystem resilience, improve human well-being, and secure a more sustainable future for present and future generations.

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# Genetics and Molecular Approaches in Wildlife Conservation

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## Abstract

Wildlife populations are increasingly threatened by habitat fragmentation, overexploitation, climate change, pollution, emerging diseases and invasive species. These pressures reduce population size and disrupt gene flow, leading to inbreeding, genetic drift, loss of adaptive variation and increased extinction risk. Genetics and molecular biology provide powerful tools for identifying species, assessing genetic diversity, reconstructing population histories, detecting illegal wildlife trade, monitoring pathogens and designing scientifically informed conservation programmes. Traditional markers such as mitochondrial DNA, microsatellites and amplified fragment length polymorphisms have been complemented by single-nucleotide polymorphisms, whole-genome sequencing, environmental DNA, metabarcoding, transcriptomics and epigenomics. These approaches support the identification of conservation units, wildlife corridors, genetically suitable founders and candidates for genetic rescue. However, genomic evidence must be integrated with ecological, behavioural, demographic and local knowledge. This chapter reviews the principles, methods, applications, limitations and prospects of genetics and molecular approaches in wildlife conservation.

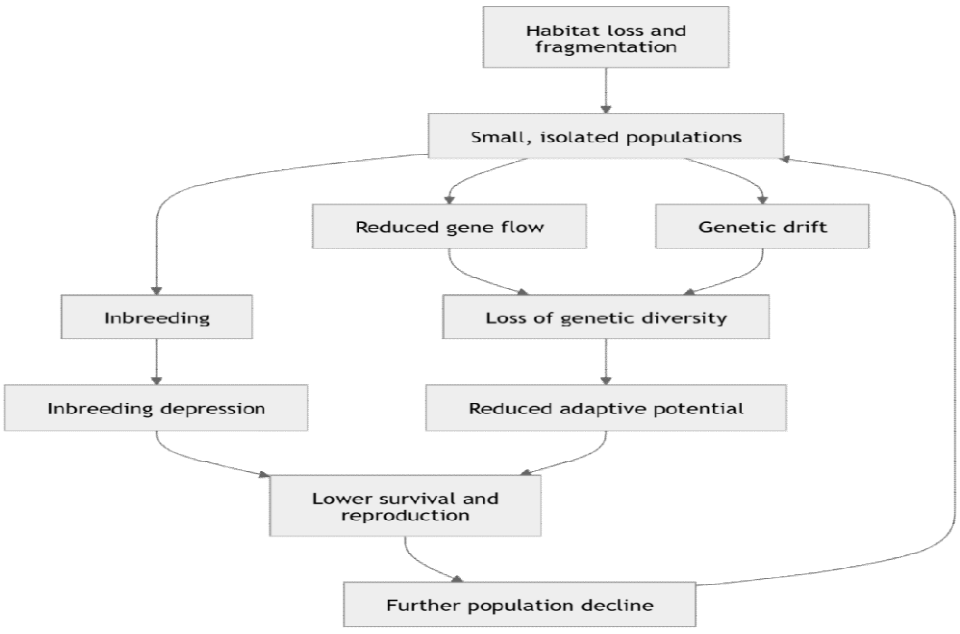
**Keywords:** conservation genetics, wildlife genomics, genetic diversity, inbreeding, environmental DNA, DNA barcoding, population structure, genetic rescue, wildlife forensics

## Introduction

Wildlife conservation traditionally relied on field surveys, morphology, behaviour, habitat assessment and population counting. Although these methods remain indispensable, they may not reveal the evolutionary processes influencing the long-term survival of wildlife populations. Two populations may contain similar numbers of animals but differ substantially in genetic diversity, relatedness, adaptive potential and disease susceptibility. Genetics therefore adds an important evolutionary dimension to wildlife conservation.Conservation genetics applies genetic principles and molecular techniques to the protection and management of biodiversity. Its principal objectives are to preserve genetic diversity, reduce harmful inbreeding, maintain evolutionary potential, identify conservation units and clarify taxonomic

uncertainties (Frankham et al., 2010; Allendorf et al., 2022). Conservation genomics extends this approach by examining thousands or millions of loci distributed throughout the genome.Small and fragmented populations are particularly vulnerable to genetic drift. Random loss of alleles reduces genetic variation, while mating among relatives increases homozygosity and exposes deleterious recessive alleles. These processes can reduce survival, fertility, disease resistance and adaptability, creating an "extinction vortex" in which demographic and genetic deterioration reinforce each other (Gilpin & Soulé, 1986; Frankham, 2005).Effective population size, denoted by $N_e$, is particularly important because it determines the rates of genetic drift and inbreeding. It is generally smaller than the observed census population, $N_c$, owing to unequal sex ratios, fluctuations in population size and variation in reproductive success. Thus, a population containing hundreds of animals may behave genetically like a much smaller population. $N_e$is the number of individuals in an idealized population that would experience the same level of genetic drift as the population under investigation (Waples, 2022). Advances in sequencing technologies now enable DNA to be obtained from hair, feathers, faeces, shed skin, saliva, museum specimens, soil and water. Consequently, researchers can study rare or elusive animals without capturing them. Environmental DNA, or eDNA, can reveal the occurrence, distribution and sometimes genetic composition of aquatic and terrestrial organisms. Genomic tools can also identify adaptive variants, reconstruct demographic histories and evaluate the outcomes of reintroduction or genetic-rescue programmes. For example, genome-wide studies of Isle Royale wolves have demonstrated the severe consequences of isolation and inbreeding in a small wildlife population (Robinson et al., 2019).

**Figure 1. Interaction of genetic and demographic threats**



**Importance of Genetic Diversity**

Genetic diversity represents heritable variation within individuals, populations and species. It provides the biological foundation for evolutionary adaptation to changing environmental conditions. Populations with greater functional genetic variation may be better able to respond to novel pathogens, rising temperatures, altered precipitation, habitat change and other environmental pressures.

Genetic diversity is commonly evaluated through:

1. **Allelic richness:** the average number of alleles present at genetic loci.
2. **Observed heterozygosity ($H_O$):** the proportion of heterozygous individuals.
3. **Expected heterozygosity ($H_E$):** heterozygosity expected under random mating.
4. **Nucleotide diversity:** average sequence difference between DNA molecules.
5. **Inbreeding coefficient:** departure from expected heterozygosity caused by related mating.
6. **Runs of homozygosity:** long, continuous homozygous genomic regions indicating common ancestry.
7. **Effective population size:** genetically effective size of the breeding population.

The expected decline in heterozygosity caused by genetic drift can be approximated by:

$$H_t = H_0 \left(1 - \frac{1}{2N_e}\right)^t$$

where $H_0$is initial heterozygosity, $H_t$is heterozygosity after $t$generations and $N_e$is effective population size. The equation illustrates why genetic variation declines more rapidly in small populations.Genetic diversity should not be treated merely as a laboratory measurement. It is relevant to reproduction, immune response, development, physiology and adaptation. Nevertheless, high neutral diversity does not always guarantee population viability, and low diversity does not inevitably lead to immediate extinction. Genetic results must therefore be interpreted together with population trends, habitat quality, reproductive biology and identified threats.

**Genetic Consequences of Wildlife Population Decline**

Genetic drift is the random change in allele frequencies between generations. It is strongest in small populations and can eliminate rare alleles regardless of whether they are advantageous. Repeated bottlenecks accelerate the loss of genetic variation.

Inbreeding occurs when related individuals reproduce. It increases homozygosity and can expose harmful recessive variants. The resulting decline in biological fitness is known as inbreeding depression. Its effects may include:

1. Reduced fertility and litter size
2. Lower juvenile survival
3. Developmental abnormalities
4. Reduced sperm quality
5. Impaired immune function
6. Greater susceptibility to environmental stress

Genome sequencing of highly inbred Isle Royale wolves identified extensive runs of homozygosity and damaging variants associated with skeletal abnormalities, illustrating how prolonged isolation can influence wildlife health (Robinson et al., 2019).

A bottleneck is a sudden reduction in population size caused by hunting, disease, habitat destruction, environmental disaster or other disturbances. Even when population numbers subsequently recover, lost alleles may not be restored. Genetic tests can detect historical and recent bottlenecks through heterozygosity patterns, allele-frequency distributions and genomic coalescent analysis.

Fragmentation divides a continuous population into small subpopulations. Restricted dispersal reduces gene flow and increases genetic differentiation. Molecular estimates of migration can help identify functional corridors and barriers that may not be evident from landscape maps alone.

Small populations may lose not only neutral diversity but also functional variants influencing immunity, metabolism, reproduction and environmental tolerance. This reduces their capacity to adapt to rapidly changing conditions.

**Sources of DNA in Wildlife Research**

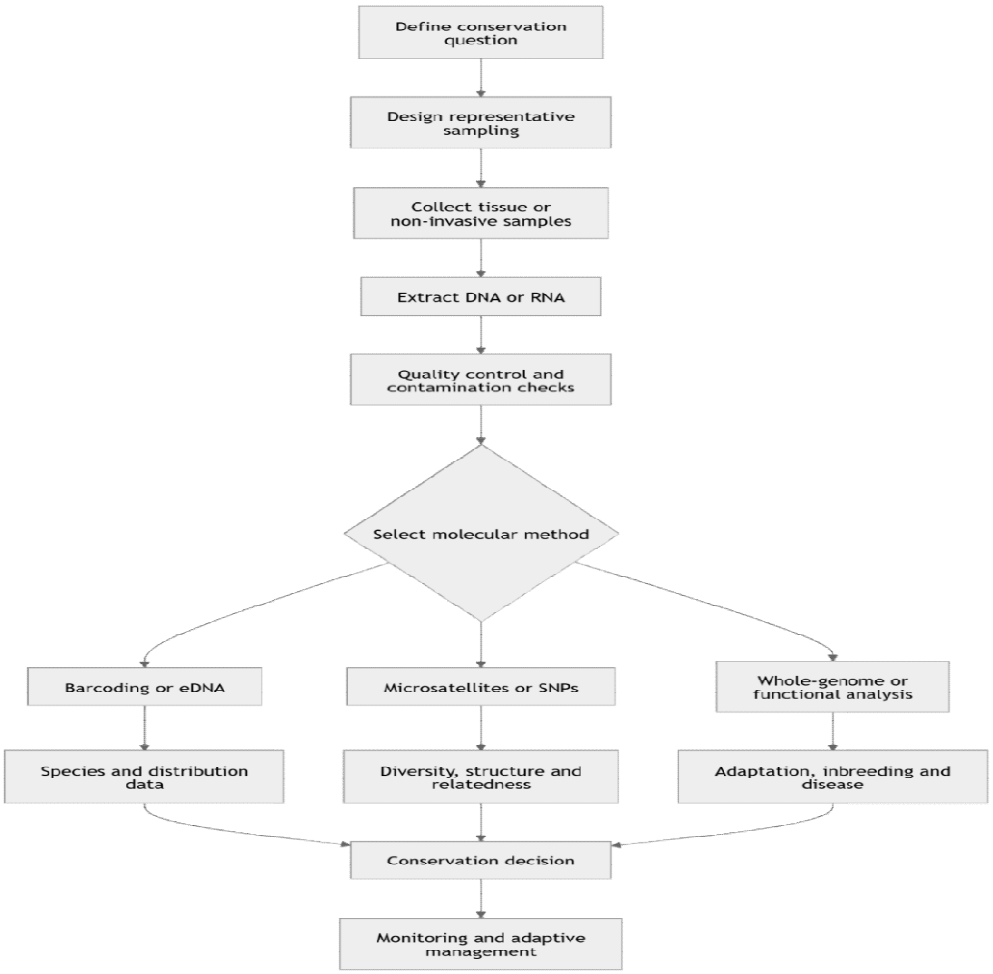
**Table 1: Wildlife genetic studies use both invasive and non-invasive biological samples.**

| Sample type | Examples | Major advantages | Important limitations |
|---|---|---|---|
| Invasive | Blood, tissue, biopsy | High-quality and high-quantity DNA | Capture, permits and animal stress |
| Non-invasive | Hair, feathers, faeces, saliva, urine | Minimal disturbance; useful for rare animals | Low DNA quantity and contamination |

| Sample type | Examples | Major advantages | Important limitations |
|---|---|---|---|
| Environmental | Water, soil, sediment, air | Detects organisms without direct observation | DNA transport and false detection |
| Historical | Museum skin, bone, tooth, horn | Provides temporal and extinct-population data | Fragmented DNA and contamination |
| Forensic | Meat, skin, scales, claws, ivory | Identifies species and geographic origin | Chain-of-custody requirements |

Non-invasive samples are particularly valuable for elusive, nocturnal, dangerous or endangered animals. However, they often contain degraded DNA, PCR inhibitors and DNA from non-target species. Strict laboratory controls, replication and validated reference databases are essential.

**Figure 2. Molecular workflow for wildlife conservation**



**Molecular Markers Used in Wildlife Conservation**

Mitochondrial DNA is maternally inherited in most animals, occurs in many copies per cell and is relatively easy to amplify from degraded samples. Genes such as cytochrome c oxidase subunit I (COI), cytochrome *b*and the control region are widely used for species identification, phylogeography and maternal-lineage analysis.Its limitations include maternal inheritance, absence of recombination and representation of only one evolutionary history. Mitochondrial evidence should therefore be supplemented with nuclear markers when possible.

DNA barcoding identifies organisms using a standardised, short DNA sequence. The mitochondrial COI gene is commonly used in animals. Barcoding helps:

1. Identify cryptic and morphologically similar species
2. Recognise illegally traded wildlife products
3. Identify eggs, larvae, feathers, meat or processed material
4. Validate field identifications
5. Build biodiversity inventories

A barcode match is only as reliable as its reference database. Incorrectly identified reference specimens can lead to misleading results.

Microsatellites are short tandemly repeated nuclear DNA sequences. Their high polymorphism makes them useful for estimating genetic diversity, parentage, relatedness, population structure and migration. They have been widely applied in conservation programmes because they require comparatively modest laboratory resources.Their disadvantages include scoring errors, null alleles, limited comparability among laboratories and the relatively small number of loci examined.

SNPs are single-base variations distributed across the genome. Although individual SNPs are usually biallelic, thousands can be analysed simultaneously. They provide reproducible information about ancestry, population structure, inbreeding, hybridisation, gene flow and adaptive variation.

Methods such as RAD-seq and genotyping-by-sequencing analyse a selected fraction of the genome. They provide large numbers of markers without requiring the cost of sequencing every genome completely. However, missing data and differences in laboratory protocols can complicate comparisons.

Whole-genome sequencing examines nearly the complete genetic information of an organism. It can identify:

1. Genome-wide heterozygosity
2. Runs of homozygosity

3. Deleterious mutations
4. Historical changes in population size
5. Introgression and hybridization
6. Regions associated with environmental adaptation
7. Immune-system and reproductive variation

Large international programmes such as the Earth BioGenome Project aim to create genomic resources across eukaryotic biodiversity, offering important reference data for conservation research (Lewin et al., 2018).

**Table 2. Comparison of major molecular approaches**

| Approach | Primary application | Resolution | Relative cost |
|---|---|---|---|
| Mitochondrial sequencing | Lineage and species identification | Low–moderate | Low |
| DNA barcoding | Species identification | Moderate | Low |
| Microsatellites | Diversity, parentage and structure | Moderate | Low–moderate |
| SNP panel | Structure, ancestry and monitoring | High | Moderate |
| RAD-seq/GBS | Population genomics | High | Moderate |
| Whole-genome sequencing | Inbreeding, adaptation and mutation load | Very high | High |
| eDNA/metabarcoding | Species or community detection | Variable | Moderate |
| Transcriptomics | Gene-expression responses | High | Moderate–high |

## Population Genetic and Genomic Applications

Correct taxonomy is fundamental to conservation. Morphologically similar populations may represent distinct species, whereas apparently different forms may belong to a single variable species. Molecular phylogenetics, DNA barcoding and genome-scale analysis can reveal cryptic species and evolutionarily distinct lineages.Molecular evidence should not be used alone to redefine species. Integrative taxonomy combines genetics with morphology, ecology, behaviour, geography and reproductive evidence.Genetic differentiation indicates how populations are connected by reproduction and dispersal. Common statistics include $F_{ST}$, analysis of molecular variance and clustering or ancestry models. These analyses can identify:

1. Isolated populations
2. Dispersal barriers
3. Source and sink populations
4. Wildlife corridors
5. Migratory connectivity
6. Units requiring separate management

Landscape genetics combines genetic data with spatial variables such as rivers, roads, settlements, elevation and vegetation cover. This helps determine which landscape features facilitate or restrict movement.

Genetic information assists in defining:

1. **Evolutionarily Significant Units:** historically isolated lineages with distinctive evolutionary characteristics.
2. **Management Units:** populations that are demographically or genetically differentiated enough to require separate management.
3. **Adaptive units:** populations possessing locally important adaptive variants.

Excessive splitting can create very small management populations, whereas inappropriate mixing can disrupt local adaptation. Management boundaries should therefore reflect the conservation objective and available biological evidence.Parentage analysis is important in captive breeding, reintroduction and intensively managed wild populations. It helps avoid close-relative matings, balance founder representation and maintain maximum genetic diversity.Genomic data can reconstruct past population expansions, contractions, divergence and migration. These results help distinguish naturally low diversity from recent human-induced genetic erosion.

**Environmental DNA and Metabarcoding**

Environmental DNA consists of genetic material released by organisms into water, soil, sediment, snow or air. Sources include mucus, skin cells, faeces, urine, gametes and decomposing tissues.

Two principal approaches are used:

1. **Targeted eDNA assays:** detect one species using species-specific primers or probes.
2. **eDNA metabarcoding:** amplifies standardised markers from many organisms to characterise biological communities.

eDNA can detect rare, invasive, endangered or difficult-to-observe species. It is particularly valuable for fishes, amphibians, aquatic reptiles and freshwater invertebrates. Population-level eDNA analysis is also developing; research has demonstrated that aquatic eDNA can reveal genetic diversity and population structure, although its accuracy depends on DNA concentration, marker design and environmental transport (Andres et al., 2023).Important limitations include contamination, PCR inhibition, incomplete reference libraries and uncertainty regarding the location and time of DNA release. Positive detection indicates the presence of DNA, but not necessarily a living individual at the precise sampling location. Hydrology-based models may be required to interpret eDNA movement in rivers (Carraro et al., 2018).

**Molecular Approaches in Wildlife Forensics**

Illegal wildlife trade threatens numerous species. Wildlife forensic genetics can determine:

1. Species identity
2. Individual identity
3. Sex of an animal
4. Population or geographic origin
5. Parentage
6. Whether samples originate from the same individual
7. Whether wildlife products are authentic or substituted

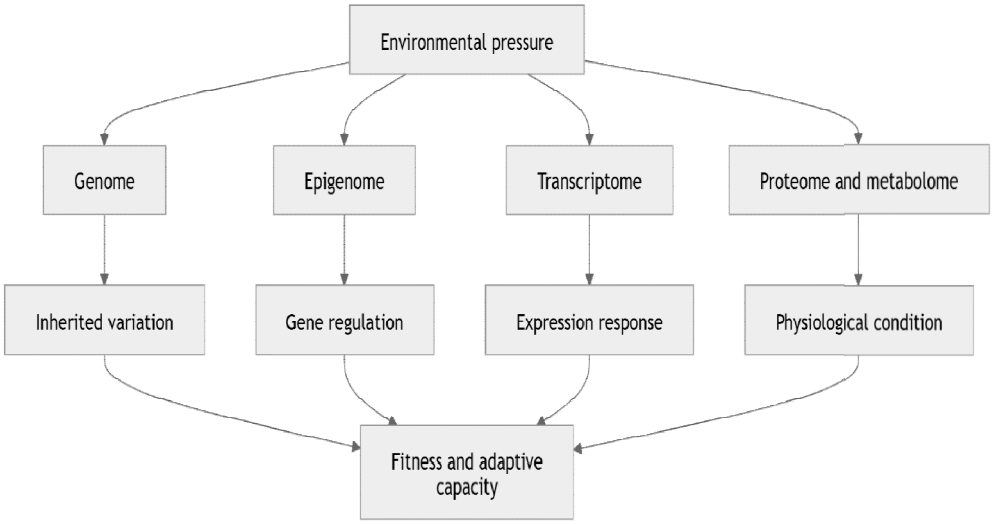
DNA barcoding is especially useful for identifying processed meat, powders, scales, skins and traditional medicinal products in which morphological characteristics are absent. Microsatellites and SNP panels may link seized materials to individuals or populations.Forensic evidence requires standardised sampling, validated assays, a secure chain of custody, quality assurance, and careful interpretation. Reference datasets must include adequate geographic and genetic representation.

**Conservation Genomics and Adaptive Variation**

Neutral markers describe population history and gene flow, but they may not directly reveal adaptation. Conservation genomics can locate variants associated with climate, altitude, salinity, disease resistance, diet or other environmental factors.Genome–environment association analysis compares allele frequencies with environmental variables. Common-garden studies and functional validation are then needed to distinguish adaptation from population history. Transcriptomics examines changes in gene expression, while proteomics and metabolomics evaluate proteins and metabolic products. Together, these methods improve understanding of wildlife responses to

stress.Epigenetic modifications, including DNA methylation, can change gene activity without altering the DNA sequence. They may influence rapid responses to pollution, captivity, nutrition and climate. However, the stability and heritability of many epigenetic changes remain uncertain.

**Diagram 1. Multi-omics approach to wildlife health**




## Genetic Rescue and Assisted Gene Flow

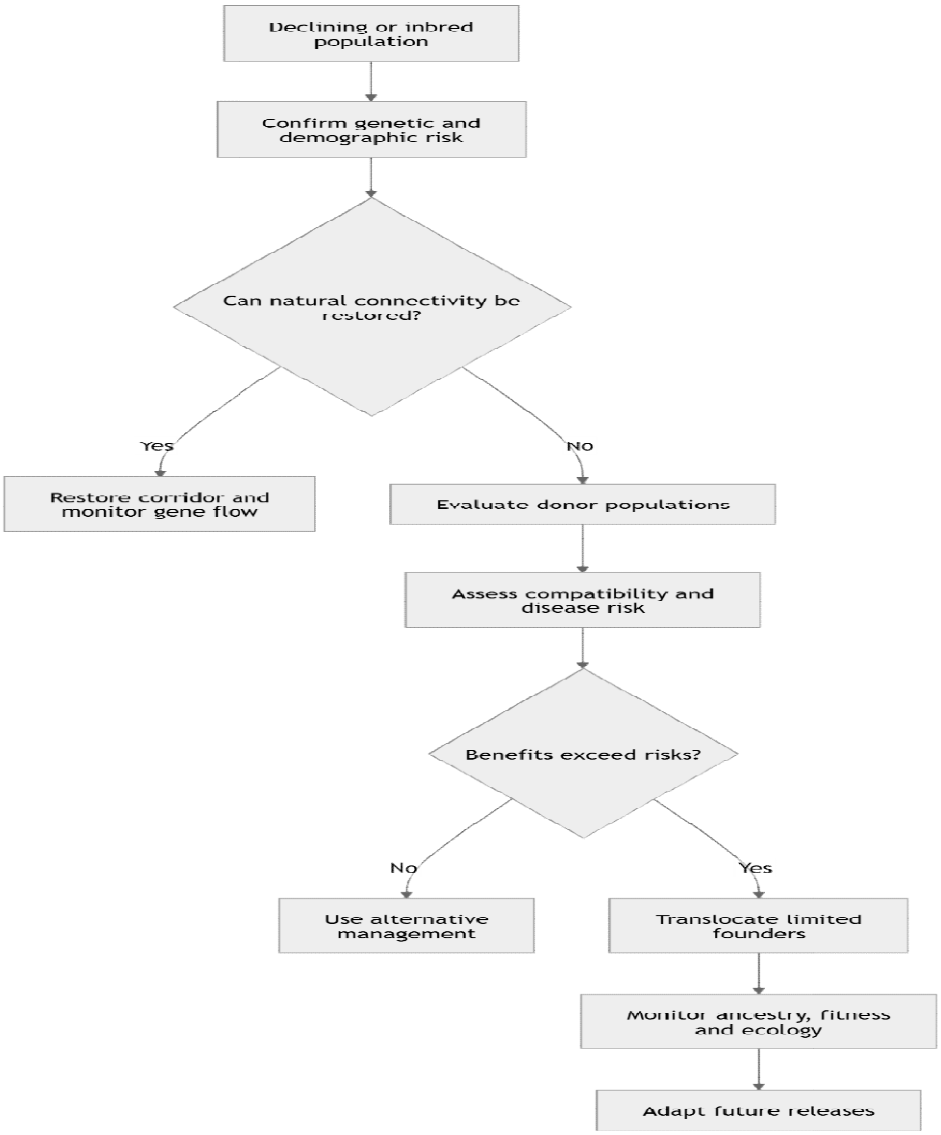
Genetic rescue is the intentional movement of individuals or genetic material into an inbred population to increase genetic variation and improve fitness. Assisted gene flow may also introduce variants expected to enhance adaptation to future environmental conditions.

Potential benefits include:

1. Increased heterozygosity
2. Reduced inbreeding
3. Improved survival and reproduction
4. Restoration of adaptive variation
5. Increased effective population size

Possible risks include outbreeding depression, disruption of local adaptation, disease introduction and demographic displacement. The source and recipient populations should therefore be compared for ecological compatibility, chromosomal differences, evolutionary history and pathogen status.The widely cited Florida panther programme demonstrated how introducing individuals from another population could improve genetic variation and demographic performance. However, the outcomes and interpretation of genetic-rescue projects require continued monitoring. Genetic rescue should complement habitat restoration and threat reduction, not replace them.

**Flowchart 1. Decision framework for genetic rescue**




## Captive Breeding and Reintroduction

Captive populations may lose genetic diversity because they are founded by few animals and maintained for several generations under artificial conditions. Genetic management seeks to:

1. Minimise mean kinship
2. Equalise founder contribution
3. Avoid close-relative mating
4. Retain rare alleles
5. Prevent unplanned hybridisation
6. Preserve behaviour needed for survival in nature
7. Reduce adaptation to captivity

Pedigrees can be supplemented by molecular parentage analysis when ancestry is uncertain. Genome-wide markers provide more accurate estimates of relatedness than pedigrees alone, particularly when founders are unknowingly related.Before reintroduction, genetic data can determine whether released animals correspond to the appropriate geographic lineage. After release, non-invasive genotyping can monitor survival, reproduction, dispersal and integration with resident populations.

**Molecular Detection of Wildlife Diseases**

Emerging infectious diseases are major causes of wildlife decline. Molecular techniques used in wildlife health include:

1. Conventional and quantitative PCR
2. Reverse-transcription PCR for RNA viruses
3. Metagenomic sequencing
4. Pathogen barcoding
5. Microbiome analysis
6. Host immune-gene analysis
7. Wastewater and environmental pathogen surveillance

Molecular diagnosis enables detection of pathogens before clinical signs become widespread. Metagenomics can identify unexpected or novel organisms without requiring a species-specific test. Genetic analysis also helps determine routes of pathogen transmission among wildlife, livestock and humans, supporting the One Health approach.However, detection of pathogen DNA or RNA does not always demonstrate active infection. Results should be interpreted alongside pathology, culture, serology, clinical signs and epidemiological evidence.

**Emerging Technologies**

Hand-held sequencers make field-based DNA analysis increasingly possible. They can support rapid species identification, pathogen surveillance and anti-poaching investigations, although reliable field extraction and bioinformatics remain challenging.Machine learning can integrate genomic, environmental, demographic and remote-sensing data. Potential applications include predicting population vulnerability, identifying adaptive variants and prioritising corridors. Models require representative training data and transparent validation.

Genome editing, cloning, cryopreservation, artificial insemination and germ-cell technologies may eventually support highly threatened species. Gene editing has been discussed for correcting harmful mutations, controlling invasive populations and increasing disease resistance. Nevertheless, ecological uncertainty, off-target effects, animal welfare, governance and ethical concerns currently limit direct application to

wildlife conservation.Frozen tissue, DNA, sperm, ova, embryos and cell cultures preserve genetic material for research and possible future assisted reproduction. Biobanks should maintain detailed metadata, legal documentation and equitable access arrangements.

**Ethical, Legal and Social Considerations**

Wildlife genomics is not value-neutral. Genetic data may reveal the locations of endangered animals, making them vulnerable to poaching. Samples and sequence data may also be connected to the biological resources and knowledge of Indigenous peoples and local communities.

Responsible research should address:

1. Collection and transport permits
2. Animal-welfare standards
3. International agreements and access regulations
4. Benefit-sharing
5. Data ownership and sovereignty
6. Protection of sensitive location information
7. Transparent participation of local communities
8. Long-term storage and responsible reuse of samples

Genomic information should support conservation partnerships rather than exclude communities that protect and depend upon wildlife resources.

**Limitations and Challenges**

Despite their value, molecular approaches have several limitations:

1. **Sampling bias:** easily accessible areas or individuals may not represent the whole population.
2. **Small sample size:** estimates of diversity and differentiation may be unreliable.
3. **Poor-quality DNA:** non-invasive and historical samples are often degraded.
4. **Reference bias:** results may depend heavily on the available reference genome.
5. **Incomplete databases:** species identification may fail when reference sequences are absent.
6. **High computational requirements:** genome-scale analysis needs expertise and infrastructure.

7. **Statistical uncertainty:** demographic history and selection can produce similar genomic patterns.
8. **Limited ecological interpretation:** genetic differentiation does not automatically identify its ecological cause.
9. **Unequal access:** high costs may exclude researchers and institutions in biodiversity-rich regions.
10. **Management gap:** technically advanced results may not be translated into practical conservation action.

**Integrated Framework for Wildlife Conservation**

Genetic data are most useful when combined with ecological, demographic and spatial information.

An effective programme should proceed through the following stages:

1. Define the conservation question before choosing a molecular technique.
2. Develop representative spatial and temporal sampling.
3. Select markers appropriate to the species, sample quality and decision required.
4. Apply laboratory controls and reproducible bioinformatics.
5. Estimate uncertainty and test alternative explanations.
6. Integrate genomic results with ecology and demography.
7. Translate findings into realistic management actions.
8. Monitor biological outcomes and revise management accordingly.

**Conclusion**

Genetics and molecular biology have transformed wildlife conservation from a discipline focused mainly on counting organisms into one capable of examining ancestry, connectivity, evolutionary potential and biological function. DNA barcoding assists species identification and wildlife forensics; microsatellites and SNPs reveal diversity, relatedness and population structure; eDNA enables non-invasive detection; and genome sequencing identifies inbreeding, demographic history and adaptive variation.These techniques can guide habitat connectivity, captive breeding, reintroduction, genetic rescue, disease surveillance and control of illegal wildlife trade. Nevertheless, molecular information cannot substitute for habitat protection, ecological research or community participation. A genetically diverse population cannot survive without adequate habitat, while habitat protection alone may not reverse severe inbreeding or restore lost connectivity. The strongest conservation programmes therefore integrate genetics, ecology, demography, animal health and social knowledge. Used responsibly, these combined approaches can preserve both

existing wildlife diversity and its capacity to evolve under future environmental change.

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# Biodiversity with Special Reference to the Tarai Region of Devipatan Mandal

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**Abstract**

The Tarai region of Devipatan Mandal, comprising the districts of Bahraich, Balrampur, Shravasti, and Gonda, represents one of the most ecologically significant landscapes of northern India. Situated along the Indo-Nepal border in the Himalayan foothill zone, the region is characterized by fertile alluvial soils, dense forests, wetlands, grasslands, and riverine ecosystems that support rich biological diversity. The entire Devipatan Mandal falls within the Tarai belt, which serves as a transitional ecological zone between the Himalayan mountains and the Gangetic plains.

The present study examines the biodiversity status of the Tarai region with special emphasis on its floral and faunal wealth, ecological significance, conservation challenges, and sustainable management strategies. The region contains important protected areas such as Katarniaghat Wildlife Sanctuary and Suhaildev Wildlife Sanctuary, which provide habitats for numerous endangered and threatened species. The forests and wetlands support species such as the Bengal tiger, leopard, swamp deer, Gangetic dolphin, gharial, python, otter, and a wide variety of resident and migratory birds. The Tarai ecosystem is also recognized for its extensive Sal forests, grasslands, marshes, and aquatic habitats that maintain ecological balance and biodiversity conservation.

**Key words:** Biodiversity, Tarai Region, Devipatan Mandal, Flora, Fauna, Conservation, Wetlands, Forest Ecosystem, Uttar Pradesh, Sustainable Development.

## Introduction

Biodiversity refers to the variety and variability of living organisms present on Earth, including plants, animals, microorganisms, and the ecosystems in which they live. It encompasses three major levels: **genetic diversity, species diversity, and ecosystem diversity**. Biodiversity is essential for maintaining ecological balance, supporting human livelihoods, and ensuring the sustainability of natural resources.

The Tarai region of northern India is one of the richest biodiversity zones of the country. Among the important Tarai areas, the **Devipatan Mandal** of Uttar Pradesh occupies a significant place because of its unique geographical location, fertile alluvial soils, extensive forests, wetlands, rivers, and wildlife habitats. The region includes the districts of **Bahraich, Balrampur, Shravasti, and Gonda** and shares an international boundary with Nepal. The entire division is considered a part of the Tarai belt and is characterized by dense forests, grasslands, marshes, and river systems.

## Meaning and Importance of Biodiversity

Floral diversity in the region is equally remarkable, with studies documenting hundreds of tree species and numerous medicinal plants, shrubs, climbers, lichens, and grasses. Research conducted in the Tarai districts of Bahraich and Balrampur has revealed significant species richness, including several new records of lichens for Uttar Pradesh and India. The vegetation is dominated by Sal (Shorea robusta), Sheesham, Khair, Jamun, Haldu, and various grassland species that provide essential ecological services.

Despite its ecological importance, the region faces serious threats from deforestation, agricultural expansion, habitat fragmentation, illegal hunting, invasive species, and climate change. Increasing human pressure on forest resources has adversely affected wildlife habitats and ecosystem stability. Conservation initiatives, protected-area

management, community participation, and sustainable resource utilization are therefore essential for preserving the unique biodiversity of the Tarai landscape.

Biodiversity serves several important functions:

1. **Ecological Stability:** It maintains ecosystem balance through food chains and nutrient cycles.
2. **Economic Benefits:** Provides timber, fuel, fodder, medicines, and agricultural resources.
3. **Climate Regulation:** Forests absorb carbon dioxide and help regulate climate.
4. **Soil Conservation:** Vegetation prevents soil erosion and maintains soil fertility.
5. **Scientific and Educational Value:** Biodiversity offers opportunities for research and environmental education.
6. **Cultural Importance:** Many species and ecosystems are linked with local traditions and beliefs.

**Review of Literature on Biodiversity of Devipatan Mandal and Their Findings**

The Tarai region of Devipatan Mandal (comprising Bahraich, Balrampur, Shravasti, and Gonda districts of Uttar Pradesh) is characterized by rich forests, wetlands, grasslands, and riverine ecosystems. Several studies have examined its biodiversity, flora, fauna, wetlands, and conservation challenges.

**1. Panigrahi, G., Singh, A.N. & Mishra, O.P. (1969)**

**Title:** Contribution to the Botany of the Tarai Forests of Bahraich District, Uttar Pradesh

**Major Findings**

- Provided one of the earliest scientific descriptions of Tarai forest vegetation.
- Documented diverse tree species, shrubs, grasses, and medicinal plants.
- Highlighted the ecological importance of moist deciduous forests and swamp vegetation.
- Established baseline information for future biodiversity studies in the Tarai region.

**2. Deshpande et al. (1971)**

**Title:** Mollisols of Tarai Region of Uttar Pradesh: Morphology and Mineralogy

**Major Findings**

- Described the fertile alluvial soils of the Tarai region.
- Reported that the area was historically covered by dense forests and wetlands.
- Demonstrated that rich soil and high groundwater levels support diverse vegetation communities.

**3. Agarwal and Associates (Tarai Soil Studies)**

**Major Findings**

- Explained the relationship between soil characteristics and vegetation distribution.
- Found that poorly drained soils support wetland biodiversity, while better-drained soils support forest ecosystems.
- Suggested that habitat diversity is largely controlled by hydrological conditions.

**4. Kumar, Bajpai, Mishra et al. (2011)**

**Title:** Assessment of Diversity in the Genus Ficus of Katerniaghat Wildlife Sanctuary

**Major Findings**

- Recorded 11 species of Ficus in the sanctuary.
- Identified several species not previously reported from the area.
- Highlighted the ecological significance of Ficus species as keystone resources for birds and mammals.

**5. Gupta, V., Gupta, N., Nayaka, S. et al. (2023)**

**Title:** New Records of Lichens from Uttar Pradesh

**Major Findings**

- Conducted surveys in Bahraich and Balrampur districts of the Tarai region.
- Recorded 34 lichen species.
- Reported ten species as new records for Uttar Pradesh and two species as new records for India.
- Demonstrated that the Tarai region harbors previously undocumented cryptogamic biodiversity.

**6. Sanjay, M.C. & Prakash, S. (2020)**

**Title:** Ichthyofaunal Diversity of Rapti River Flowing Through Shravasti and Balrampur Districts

**Major Findings**

- Recorded 46 fish species belonging to 30 genera, 19 families, and 9 orders.
- Family Cyprinidae showed the highest diversity.
- Identified overfishing and pollution as major threats.
- Recommended urgent conservation measures for aquatic biodiversity.

**7. Studies on Katerniaghat Wildlife Sanctuary**

**Major Findings**

- Documented rich mammalian diversity including:
  - Bengal Tiger
  - Leopard
  - Swamp Deer
  - Gangetic Dolphin
- Reported high avian diversity due to the mosaic of wetlands and forests.
- Established the sanctuary as one of the most significant biodiversity hotspots in Uttar Pradesh.

**8. Chaurasia, A.K., Choubey, A.K. & Rai, G. (2021)**

**Title:** Cropping Pattern and Diversification in the Tarai Region of Uttar Pradesh

**Major Findings**

- Examined land-use changes in the Tarai region.
- Found increasing agricultural expansion and crop diversification.
- Suggested that habitat conversion is reducing natural biodiversity in some areas.
- Recommended sustainable land-use planning for biodiversity conservation.

**Research Gaps Identified**

The literature reveals several important gaps:

1. Limited district-level biodiversity inventories for Balrampur and Shravasti.
2. Insufficient studies on insect diversity and pollinators.
3. Lack of long-term monitoring of wetland ecosystems.
4. Limited GIS-based biodiversity mapping.
5. Inadequate assessment of climate change impacts on Tarai biodiversity.
6. Need for integrated studies linking biodiversity, livelihoods, and conservation.

## Overall Conclusions from Literature

- The Tarai region of Devipatan Mandal is one of the richest biodiversity zones of Uttar Pradesh due to its forests, wetlands, rivers, and fertile alluvial plains.
- The region supports diverse flora, lichens, fishes, mammals, birds, and wetland species.
- Katerniaghat forests and the Rapti River are major biodiversity reservoirs.
- Habitat degradation, agricultural expansion, pollution, and overexploitation are the principal threats to biodiversity.
- Existing studies emphasize the need for conservation planning, sustainable resource use, and scientific monitoring to preserve the biodiversity of the Devipatan Tarai region.

## The Tarai Region of Devipatan Mandal

The Tarai is a low-lying belt situated at the foothills of the Himalayas. It is characterized by marshy lands, abundant groundwater, high rainfall, and fertile soils. The region developed from alluvial deposits brought by Himalayan rivers and was historically covered by dense forests and swampy vegetation.

The Devipatan Mandal possesses several geographical features that promote biodiversity:

- Proximity to the Himalayan foothills.
- High annual rainfall and humid climate.
- Numerous rivers such as Ghaghra, Rapti, Budhi Rapti, Suan, Kuano, and Bhakla.
- Extensive forest cover and grasslands.
- Wetlands and marshy ecosystems.

## Ecosystem Diversity in Devipatan Tarai

The study concludes that the Tarai region of Devipatan Mandal is a biodiversity hotspot of Uttar Pradesh and plays a vital role in maintaining ecological balance, supporting livelihoods, and conserving genetic resources. Effective conservation policies integrating ecological, social, and economic dimensions are necessary to

ensure the long-term sustainability of this invaluable natural heritage. The biodiversity of the region is supported by diverse ecosystems:

**1. Forest Ecosystems**

The forests are dominated by **Sal (Shorea robusta)**, Teak, Shisham, Khair, Semal, and various shrubs and climbers. These forests provide habitat to numerous wildlife species.

**2. Grassland Ecosystems**

Tall grasslands are characteristic of the Tarai landscape. These grasslands support herbivorous animals such as deer and provide nesting grounds for many bird species.

**3. Wetland Ecosystems**

Numerous marshes, ponds, swamps, and riverine wetlands serve as breeding and feeding grounds for fish, reptiles, amphibians, and migratory birds.

**4. Riverine Ecosystems**

The Rapti and Ghaghra river systems sustain aquatic biodiversity including fishes, turtles, crocodiles, and the endangered Gangetic dolphin.

**Floral Diversity**

The Tarai region supports rich plant diversity due to favorable climatic and soil conditions. Important plant species include:

- Sal (*Shorea robusta*)
- Teak (*Tectona grandis*)
- Shisham (*Dalbergia sissoo*)
- Khair (*Acacia catechu*)
- Bamboo species
- Semal (*Bombax ceiba*)

- Various medicinal plants and grasses

The forests also contain numerous herbs, shrubs, climbers, and medicinal plants used by local communities.

**Faunal Diversity**

**Mammals**

The Tarai forests and wildlife sanctuaries support several important mammalian species:

- Bengal Tiger
- Leopard
- Asian Elephant
- Swamp Deer (Barasingha)
- Spotted Deer
- Sambar
- Wild Boar
- Hispid Hare
- Jackal
- Fox
- Monkey and Langur species

Several of these species are threatened and receive protection within the region's wildlife reserves.

**Birds**

The region is a paradise for resident and migratory birds. Important species include:

- Bengal Florican
- Peafowl
- Hornbills

- Egrets and Herons
- Kingfishers
- Vultures
- Ducks and Geese

Wetlands and grasslands provide ideal habitats for avifaunal diversity.

**Reptiles and Amphibians**

The Tarai region is known for:

- Gharial
- Mugger Crocodile
- Turtles
- Various snake species
- Frogs and toads

The Girwa River in particular is recognized as an important habitat for the gharial.

**Aquatic Biodiversity**

The rivers and wetlands support:

- Gangetic Dolphin
- Freshwater fish species
- Crustaceans
- Aquatic insects and plankton

These organisms contribute significantly to the aquatic food web and ecosystem functioning.

**Protected Areas and Biodiversity Conservation**

**Katarniaghat Wildlife Sanctuary**

This sanctuary is one of the most important biodiversity hotspots in the Devipatan region. It covers about 400 sq. km and forms a part of the Dudhwa Tiger Reserve. The

sanctuary contains Sal forests, grasslands, wetlands, and river systems. It supports tigers, gharials, Gangetic dolphins, swamp deer, vultures, and many other endangered species.

**Suhaildev Wildlife Sanctuary**

Spread across Balrampur and Shravasti districts, this sanctuary possesses rich natural forests and significant biological diversity. The sanctuary also forms an ecological unit with forests across the Nepal border, enhancing transboundary wildlife conservation.

**Biodiversity Corridor Significance**

The Tarai forests of Devipatan act as an important ecological corridor connecting protected areas of India and Nepal. This connectivity allows movement of wildlife populations and helps maintain genetic diversity among species.

**Ecological Importance of Biodiversity in Devipatan Tarai**

**Carbon Sequestration**

Forests absorb atmospheric carbon dioxide and mitigate climate change.

**Water Regulation**

Wetlands and forests regulate groundwater recharge, flood control, and river flow systems.

**Soil Fertility**

Vegetation cover prevents erosion and enriches soil through organic matter accumulation.

**Pollination and Pest Control**

Many insects, birds, and bats contribute to pollination and natural pest management.

**Livelihood Support**

Local communities depend on forests for fuelwood, fodder, medicinal plants, and non-timber forest products.

**Threats to Biodiversity**

Despite its ecological significance, biodiversity in the Devipatan Tarai faces several challenges:

1. Deforestation and habitat destruction.
2. Agricultural expansion and monocropping.
3. Human-wildlife conflict.
4. Illegal hunting and poaching.
5. Wetland degradation.
6. River pollution.
7. Climate change and altered rainfall patterns.
8. Encroachment on forest lands.

**Conservation Measures**

**1. Geographical Setting and Ecological Significance**

The Tarai region is characterized by:

- Fertile alluvial soils deposited by Himalayan rivers.
- High groundwater levels and marshy terrain.
- Dense forests, grasslands, wetlands, and riverine ecosystems.
- Humid subtropical climate with abundant monsoon rainfall.

These geographical conditions create diverse habitats that support a rich variety of plant and animal species. The region functions as an ecological corridor connecting the forests of India and Nepal.

## 2. Forest Ecosystems and Floral Diversity

The forests of the Tarai are among the most productive ecosystems in Uttar Pradesh. Major vegetation types include:

- Sal (Shorea robusta) forests
- Teak forests
- Riverine forests
- Grasslands and swamp vegetation
- Wetland plant communities

Common tree species include Sal, Sheesham, Khair, Haldu, Jamun, Jigna, and numerous medicinal plants. These forests provide habitat, food, and shelter for wildlife while maintaining ecological balance.

## 3. Rich Faunal Diversity

The Tarai region supports a remarkable diversity of wildlife, including several endangered species.

### Mammals

- Bengal Tiger
- Leopard
- Swamp Deer (Barasingha)
- Sambar Deer
- Wild Boar
- Jackal
- Wolf
- Otter
- Hispid Hare

**Reptiles and Aquatic Fauna**

- Gharial
- Mugger Crocodile
- Python
- Various turtle species

**Aquatic Mammals**

- Gangetic Dolphin

**Birds**

The wetlands and forests attract hundreds of resident and migratory bird species such as:

- Bengal Florican
- Kingfisher
- Peacock
- Eagles
- Quails
- Black Partridge
- Owls
- Bulbuls and Mynahs

The diversity of habitats contributes to exceptionally high species richness.

**4. Wetlands and River Systems**

The geographical richness of biodiversity is strongly linked to the extensive wetland network and river systems.

Major rivers include:

- Ghaghara (Saryu)

- Rapti
- Budhi Rapti
- Kuwano
- Suwan
- Bhakla

Numerous lakes, marshes, swamps, and reservoirs provide breeding and feeding grounds for fish, amphibians, reptiles, and migratory birds. Wetlands also regulate floods and recharge groundwater.

**5. Protected Areas and Biodiversity Conservation**

**Katarniaghat Wildlife Sanctuary**

This sanctuary forms part of the Dudhwa Tiger Reserve and contains:

- Sal forests
- Grasslands
- Wetlands
- Girwa River ecosystem

It is famous for tigers, gharials, Gangetic dolphins, swamp deer, and rare birds. It also serves as an important wildlife corridor between India and Nepal.

**Suhaildev Wildlife Sanctuary**

Spread across Balrampur and Shravasti districts, this sanctuary protects:

- Natural forests
- Wetlands
- Grasslands
- Medicinal plant diversity

The sanctuary supports tigers, leopards, bears, otters, pythons, and numerous bird species.

## 6. Ecological Services of Biodiversity

The biodiversity of the Tarai region provides several ecosystem services:

- Flood mitigation through wetlands.
- Groundwater recharge.
- Carbon sequestration by forests.
- Soil conservation and erosion control.
- Climate regulation.
- Livelihood support through forest products, fisheries, and ecotourism.

These services are essential for sustainable development and human well-being in Devipatan Mandal.

## 7. Threats to Biodiversity

Despite its richness, the region faces several challenges:

- Deforestation
- Agricultural expansion
- Habitat fragmentation
- Encroachment on wetlands
- Illegal hunting
- Invasive species
- Climate change

These pressures threaten the ecological stability of the Tarai ecosystem and require effective conservation measures.

The Tarai region of Devipatan Mandal is a biodiversity hotspot of Uttar Pradesh owing to its unique geographical location, fertile alluvial plains, dense forests, extensive wetlands, and rich river systems. The coexistence of forests, grasslands, wetlands, and aquatic ecosystems supports a remarkable variety of flora and fauna, including many endangered species. Therefore, the geographical richness of

biodiversity in this region is not only an ecological asset but also a vital resource for environmental sustainability and socio-economic development.

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# Medicinal Value of *Mangifera indica*: Ethnopharmacological Insights and Therapeutic Applications

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**Abstract:**

*Mangifera indica* L. (mango) is the one of the most significant tropical fruit trees belongs to the member of the Anacardiaceae family is widely grown all over the world.Besides its nutritional value, the plant possesses significant medicinal properties and has been extensively used in the traditional systems of medicine. Various parts of the plant, including fruits, leaves, bark, seeds, flowers, and roots, contain numerous bioactive compounds that support the pharmacological actions. The major constituents of *M. indica* includes mangiferin, quercetin, catechins, gallic acid, chlorogenic acid, tannins, flavonoids, phenolic acids, triterpenoids, and carotenoids. These phytochemicals exhibit diverse biological activities such as antioxidant, anti-inflammatory, anti-inflammatory, anti-microbial, antidiabetic, anticancer, hepatoprotective and cardioprotective effects. Mango fruits are also a great source of nutritional fiber, vital minerals, and vitamins A, C, and E. Owing to its rich phytochemical profile and therapeutic potential, *Mangifera indica* remains an important plant for nutritional, medicinal, and pharmaceutical applications.

**Keywords:***Mangifera indica,* mangiferin, polyphenols, anacardiaceae, gallic acid etc.

## 1. Introduction

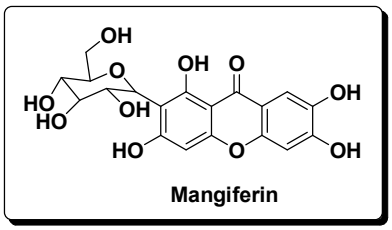
Mango biologically referred as *Magnifera indica Linn* it is a member of the Anacardiaceae family. Other important members who share the same family - Cashew (*Anacarium occidentale*), yellow and purple mombins (*Spondias mombinL.*) and (*S.*

*pupurea L.)* and Pistachio (*Pistachia vera L*)[1]. Mango is Consider as 'King of Fruits". In India, Mango tress has been referred as kalpavariksha a tree which grants wishes. Mango Fruit is an important part and Parcel of cultural heritage of India Mango tree and its fruit have a vital role in Indian religion and culture. This plant is frankly associated with the history of civilization and agricultural history. The common names of *Manginfera indica includes Mabaz in Arab, Am in Bengali, Am. Ambia, amia in Hindi, Mangas and Mau in Tamil, Mi Wang in Chinese etc.* Mango tree is evergreen, mature trees can grow to a height of 10 to 40 m and survived up to several 100 years. Mango trees that have been cultivated by selection from openly pollinated seedling pollination differ in tree size and shape [2]. Depending on cultivator, canopy can be oval, elongated or dome shaped. The bark is usually smooth, dark grey-brown to black, with shallow cracks or fissures. It peels off in thick, irregular pieces and produces a yellowish-brown gum-resin exudate. Leaves are modest, alternate, and exstipulate and the plant petiole can be varied in length from 1 to 12 cm and always distended at the base. The shapes of leaves are varied like oval-lanceolate, lanceolate, oblong, ovate, linear oblong, obovate-lanceolate or roundish oblong. Leaf size ranges from 15-45 cm in length and 5-15 cm in width. Young leaves are bronze-red, pink, tan-red, or yellow-brown and gradually turn dark green as they mature. Trees usually produce one or two growth flushes annually. The lower surface is glabrous and light green, while the upper is lustrous and dark green. The same panicle bears both male and hermaphrodite blooms, generally with more of the latter. Male and hermaphrodite blooms range in diameter from 6 to 8 mm. They smell nice, are subsessile, and are rarely pedicellate. The pollen grains range in size from 20 to 35 microns and have a variety of morphologies [4-5]. The fruit is a fleshy, roughly compressed drupe that varies greatly in size, shape, colour, presence of fiber, flavour, and taste, among additional features[3].

**2. Phytochemical Composition of *Mangifera indica***

A wide range of chemical constituents has been identified in *Mangifera indica*. The most important polyphenol which are present in abundance are xanthones, flavonoids, and phenolic acids[4]. The essential polyphenolic compounds reported from this plant include mangiferin, catechins, quercetin, gallic acid, kaempferol,

protocatechuic acid, ellagic acid, methyl and propyl gallate, rhamnetin, and anthocyanins[5].Mangiferin is one of the most well-known polyphenolic compounds found in *Mangifera indica* and has been widely investigated due to its diverse biological activities. Mangiferin was first isolated xanthone and pharmacologically investigated and possessed various biological activities.



Mangiferin

Mangiferin have xanthone skeleton in which a glucose moiety is flanked with aromatic ring. It possesses several biological activities such as antimicrobial, antioxidant, anti-diabetic, anticancer and several other properties like immunomodulatory and antiallergic etc. It is found that it enhances the monocyte-macrophage system by increasing its capacity. Mangiferin also showed activity against gram (+ve) and gram (-ve) bacteria.Other significant components include phenolic acids, quercetin, isoquercetin, ascorbic acid, benzophenones, flavonoids, carotenoids, and tocopherols, all of which contribute to *Mangifera indica* antioxidant potential. Another important group of natural compounds present in plants is carotenoids, which are responsible for the bright yellow coloration of the peel and pulp of *Mangifera indica* fruits.Mango also contains a variety of volatile compounds having low molecular weight (less than 400 Da) and belonging to different functional groups. These volatile constituents contribute significantly to the characteristic aroma of the fruit and are generally present in low amounts, usually around 50 ppm or lower. The volatile profile mainly consists of monoterpenes, sesquiterpenes, esters, and other oxygenated compounds.

**Major Phytochemicals of *Mangifera indica***

**Bark:** Mango bark is rich in polyphenols and phenolic acids, including protocatechuic acid, catechin, mangiferin, benzoic acid, gallic acid, shikimic acid, and kaempferol. It also contains terpenoid saponins (indicoside A and B) and amino acids such as alanine, glycine, and γ-aminobutyric acid (GABA).

**Leaves:** leaves contain amino acids such as glycine, alanine, valine and tyrosine along with polyphenols and phenolic compounds including gallic acid, protocatechuic acid, hyperin, catechin, quercetin, and mangiferin. They also contain alcohols (methyl, ethyl, and isobutyl alcohols) and terpenes such as α-pinene, β-pinene, taraxerol, and linalool, which contribute to their medicinal and antioxidant properties.

**Flowers:** Flowers contain amino acids like threonine, valine, alanine, and tryptophan. They also contain Polyphenols and phenolic acids contain gallic acid, Mangiferin, quercetin, and ellagic acid. Triterpenes and triterpenoids have $\beta$-pinene, nerol, limonene, phellandrene, and $\alpha$-pinene.

**Root**: The roots of *Mangifera indica* contain several triterpenes and triterpenoids, including friedelin, friedelan-3β-ol, α-amyrin, β-amyrin, and cycloartenol. They also contain sterols such as β-sitosterol and the chromone derivative 3-methoxy-2-(4-methylbenzoyl)-chromone.

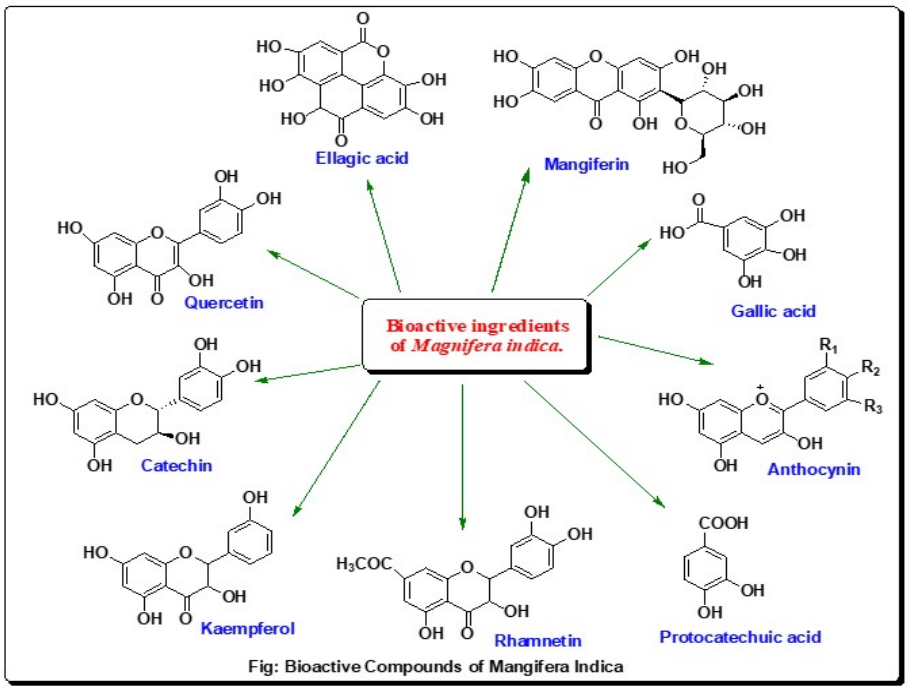


Fig: Bioactive Compounds of Mangifera Indica

## 3. Polyphenols, Flavonoids, and Vitamins

Polyphenols constitute an important group of phytochemicals that are widely distributed throughout the plant kingdom. These compounds play a significant role in plant defense mechanisms by protecting against pathogen attack, ultraviolet radiation, and reactive oxygen species (ROS)[6]**.** In mango fruit, the major antioxidant polyphenols belong mainly to the flavonoid class, including catechins, quercetin, rhamnetin, anthocyanins kaempferol, and tannic acid, as well as the xanthone compound mangiferin. The pulp of *Mangifera indica* is particularly rich in flavanols, predominantly in the form of quercetin glycosides such as glucose, galactose, rhamnose, xylose, and arabinose derivatives. Minor amounts of kaempferol, isorhamnetin, fisetin, and myricetin have also been reported[7]**.** Among the flavonoids identified upper flesh of mango, quercetin and its glycosidic derivatives are found in abundance. Fresh mango pulp contains high levels of quercetin and also its glycosides (46.6 mg/kg), while kaempferol, rhamnetin, myricetin, and fisetin occur in relatively lower concentrations[8]**.** Mango pulp is also recognized as a rich source of vitamins and minerals. As per the USDA, the pulp of mango contains both water-soluble and fat-soluble vitamins. Vitamins A and Vitamin C are present in comparatively higher amounts than vitamins B, E, and K, whereas vitamin K occurs in smaller quantities that gradually increase during fruit ripening[9]**.** Mango fruit is considered an excellent source of vitamin A and flavonoids, both of which possess strong antioxidant properties and contribute to maintaining healthy vision. Vitamin A is also necessary for preserving healthy skin and mucous membranes. In addition, mango have vitamin C, vitamin B6 (pyridoxine), and vitamin E. Consumption of vitamin C-rich foods enhances the body's defense against infectious agents and helps neutralize harmful free radicals. Vitamin B6 is important for the synthesis of GABA (gamma-aminobutyric acid) in the brain. Mango pulp further contains important micronutrients and trace elements, including calcium, phosphorus, iron, and vitamins A and C. Vitamin E, present in mango peel at concentrations ranging from 205–509 µg/g, has attracted attention for its potential application in skincare products. Notably, the vitamin E content is maximum in ripe mango peel compared to raw mango peel[10]**.**

**4**. **Pharmacological Activities of *Mangifera indica:*** *Mangifera indica* contains bioactive compounds such mangiferin, quercetin, gallic acid, catechins, and other polyphenols, it has a broad spectrum of pharmacological activities[(11)]. Among the various pharmacological activities some of them are listed below:

**Antioxidant Activity:** Mango leaves, bark, fruit, and seed kernels exhibit strong antioxidant activity. Mangiferin and phenolic compounds effectively scavenge free radicals, reduce oxidative stress, and protect cellular components from damage, thereby helping to prevent chronic diseases associated with oxidative injury.

**Anti-inflammatory Effects:** Extracts of *M. indica* have demonstrated significant anti-inflammatory activity. It produces anti-inflammatory activity by inhibiting the formation of pro-inflammatory substances include nitric oxide, prostaglandins, and cytokines. These outcomes aim in the treatment of tissue damage and inflammatory conditions.

**Antidiabetic Potential:** Mango leaves and bark are traditionally used for diabetes management. Mangiferin has been shown to reduces blood glucose levels by increasing insulin sensitivity and improve glucose metabolism. It makes a promising natural agent for controlling diabetes and help to cure its complications.

**Antimicrobial Properties:** Various parts of the mango plant possess antibacterial, antifungal, and antiviral activities. The phytochemicals present in mango extracts inhibit the growth of pathogenic microorganisms, supporting their traditional use in treating infections and promoting oral and skin health.

**Anticancer Potential:** Pharmacological data profile and research indicates that mangiferin, quercetin, and other polyphenols found in *M. indica.M. indica* exhibits anticancer properties by inducing apoptosis and inhibits tumor cell proliferation through suppressing metastasis. These compounds show potential in the prevention and supportive treatment of several types of cancer.

**5.Nutritional Profile of *Mangifera indica***

Mango fruit is rich in macronutrients, including carbohydrates, proteins (amino acids) fatty acids, lipids and various organic acids. It also provides a very good number of micronutrients which includes vitamins and minerals. In addition, mango contains several non-nutritive bioactive compounds like phenolic and polyphenols

compounds, flavonoids, carotenoids, chlorophyll and a range of volatile compounds responsible for its aroma and health-promoting properties[12].

**(a) Macronutrients:**

**(i) Carbohydrate:**

The major macronutrients present in *Mangifera indica* fruit include carbohydrates, fatty acids, proteins, lipids and amino acids. When the mango is ripe it contains nearly 15% total sugars, with sucrose, fructose, and glucose being the predominant sugars in decreasing order of concentration**.** During the pre-climacteric stage, fructose serves as the principal monosaccharide[13]**,** whereas sucrose becomes the dominant sugar as the fruit ripens. In unripe mangoes, starch is the main carbohydrate reserve. As ripening progresses, this starch undergoes hydrolysis and is converted into glucose, contributing to the sweetness of the fruit. Pectin, another important structural carbohydrate abundantly present in mango pulp, plays a significant role as a gelling agent. Pectin accumulates in immature fruits; however, its molecular weight gradually decreases during the ripening process[14]**.**

**(ii) Proteins and amino acids**

Compared with other macronutrients, *Mangifera indica* contains relatively low amounts of protein. The protein content of mango pulp varies among different cultivars and geographical regions. For instance, mangoes cultivated in Colombia contain approximately 0–0.6% protein, whereas Peruvian mango varieties possess comparatively higher protein levels ranging from 1.5–5.5%. In Java cultivars, the protein content is reported to be around 1–2%, while Indian cultivars contain relatively lower amounts, approximately 0.5–1% of total protein[15]**.**Ripe mango fruit comprises a number of amino acids, especially serine, leucine, alanine, arginine, glycine, and isoleucine. The remainder of the amino acids are only present in very small quantities.

**(iii) Lipids and fatty acids**

Lipids are present in relatively low amounts in the pulp of *Mangifera indica*; however, the mango seed and peel are recognized as important sources of fatty acids and have properties comparable to cocoa butter. These fatty acids are regarded as useful byproducts of processing mangos and have potential applications in the

pharmaceutical and food industries. The major fatty acids identified in mango kernels include palmitic, stearic, oleic, and linoleic acids, whereas lignoceric, arachidic, linolenic, and behenic acids are present in smaller quantities[16].

**(iv) Organic Acids**

Organic acids may range from low molecular weight compounds, such as oxalic and citric acids, to high molecular weight compounds like humic acids, which contain aromatic nucleus with phenolic and carboxylic functional groups. In *Mangifera indica*, the acidic property of the fruit is mainly attributed to the existence of citric and malic acids. Several other organic acids associated with the tricarboxylic acid cycle have also been identified in mango fruit, including citric, oxalic, succinic, malic, and pyruvic acids, along with muconic, gallic, tartaric, glucuronic, and galacturonic acids. Among these, citric acid is the predominant organic acid, occurring at concentrations ranging from 0.13% to 0.71% of fresh weight.

**(B) Micronutrient**

Both the Vitamin C and vitamin A are among the most important vitamins present in *Mangifera indica* fruit, and regular intake of mango can help fulfill the nutritional requirements of these essential nutrients. The concentration of vitamin C changes during the ripening process, with higher levels found in less ripe fruits compared to fully ripened mangoes. However, vitamin C content decreases rapidly within 5-7 weeks after fruit set and also declines during storage of ripe fruits at room temperature[17]. In contrast, vitamins E and K are present in comparatively smaller amounts. Mango fruit also contains several members of the vitamin B complex, which function as water-soluble enzyme cofactors and participate in various metabolic activities in both plants and humans. The B-complex vitamins identified in mango include thiamine (B1), riboflavin (B2), niacin (B3), pyridoxal, and pyridoxamine (B6) pantothenic acid (B5), pyridoxine, as well as folate or folic acid (B9). Among the B-complex vitamins, biotin (B8) is the only one not reported in mango fruit[18].

**(i) Minerals**

As per the RDA guidelines and the recommendations of the National Research Council (1989), *Mangifera indica* serves as a valuable source of essential minerals required for human health. These minerals include calcium, iron, potassium, sodium,

magnesium, phosphorus, zinc, copper, manganese, and selenium. Among these, mango pulp is particularly rich in potassium (K), phosphorus (P), and calcium (Ca), whereas sodium (Na), zinc (Zn), and iron (Fe) are present in comparatively lower amounts. In contrast, mango seeds and peels contain considerably higher concentrations of these minerals than the pulp[19].

## 6. Traditional Medicinal Uses

*Mangifera indica* is one of the most significant tropical fruit crops worldwide, and India accounts for a major share of global mango production. Different parts of the mango plant are also widely used in traditional medicine across the world.

### 6.1.Uses in Ayurveda and Folk Medicine

According to Ayurveda, different parts of the mango tree are attributed with a variety of medicinal benefits. The plant parts commonly used for therapeutic purposes include ripe and unripe fruits, seed kernels, leaves, bark, roots, resins, and flowers. In classical Ayurvedic texts, *Mangifera indica* is described as useful in conditions such as Vaman (vomiting), Atisar (diarrhea), Hridayadaha (heartburn), Raktasrava (bleeding disorders), Bhagnasandhana (bone healing), and Yoni roga (female reproductive disorders). From a modern pharmacological perspective, it has been reported to exhibit anti-lipid peroxidation, cardiotonic, hypotensive, wound-healing, immunomodulatory, antidegenerative, and antidiabeticantibacterial, antifungal, antiviral, antipyretic, and antiamoebicactivities[20].

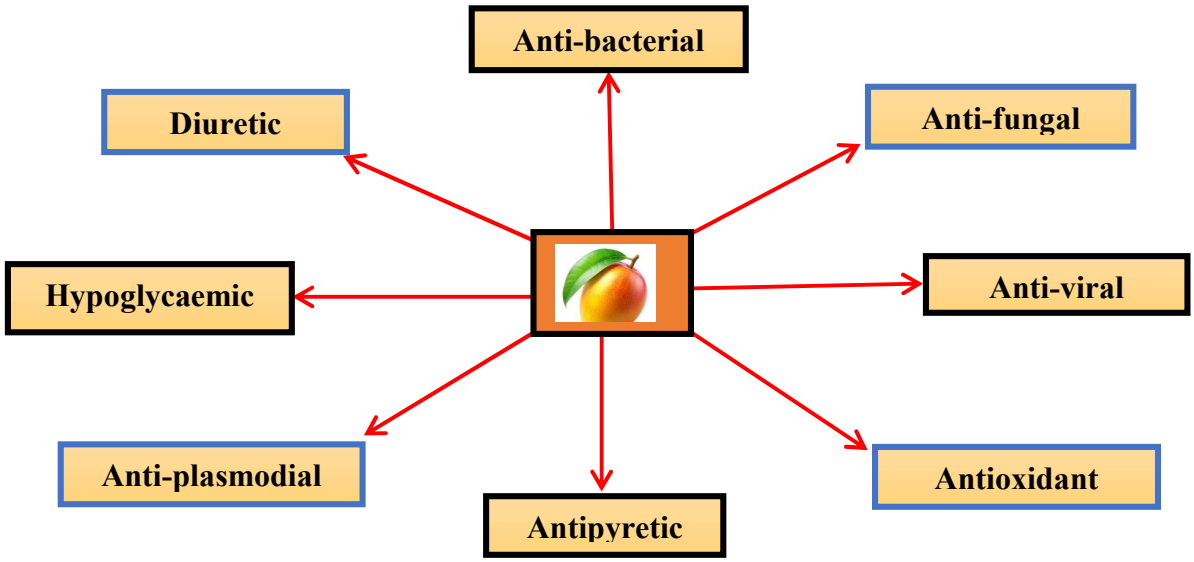



**Fig. 1.:** Various Pharmacological Activities of *Mangifera indica*

### 6.2. Therapeutic Uses of Leaves, Bark, Fruit, and Seeds

*Mangifera indica* (mango) is a versatile medicinal plant where every part of the tree like leaves, bark, fruit, and seeds provide unique therapeutic properties like antioxidant, anti-inflammatory, and antidiabetic effects[21].

Mango leaves are rich in Mangiferin, a potent antioxidant. It helps in the Diabetes management and regulate blood sugar levels and stimulate insulin production. It also helps in the Respiratory relief, Digestive health such as in the treatment of decoctions are used to treat diarrhea, dysentery, and stomach ulcers. Chewing fresh leaves can help with bleeding gums (Oral health).

Mango bark is known for its astringent, cooling properties. Gastrointestinal issues, Metabolic health like Stem bark tea is useful to treat hyperglycemia (high blood Sugar). Skin & Wounds: Bark decoctions provide as a wash for wounds, burns, and mouth sores. It also has potential property in treating rheumatism and diphtheria.

Mango fruits Both ripe and unripe fruits have distinct medicinal roles. Ripe fruits Act as a restorative tonic. It is invigorating and helps treat heat stroke.Unripe fruit have high value of Vitamin C; it increases blood vessel elasticity and stimulates bile secretion for better digestion.Mango pulp is useful in skin care like facials treatment to clean pores and prevent acne.

Mango Seeds (Kernels)are typically processed into powdered form or oil for its medicinal use. Seeds are used as a traditional remedy for asthma.Seed also has anthelmintic property, Anti-parasitic and helping in the expel intestinal worms. They are also used as Astringent i.e.used to reduce excessive bleeding from injuries or wounds[22].

## 7. Toxicity and Safety Aspects of *Mangifera indica*

*Mangifera indica* is generally safe for consumption and medicinal use when taken in recommended amounts. However, some individuals may experience allergic reactions due to urushiol-like compounds present in the peel, sap, leaves, and stem, leading to skin irritation, itching, redness, or dermatitis. Excessive consumption of ripe mangoes may cause gastrointestinal discomfort, bloating, diarrhea, and increased blood sugar levels because of their natural sugar content. Rare cases of oral allergy syndrome have also been reported. A daily intake of 150-300 g of mango pulp is

considered safe for most adults. Pregnant women, children, and diabetic patients should consult healthcare providers before using concentrated mango supplements.

## 8. Future Perspectives and Conclusion

Future research on *Mangifera indica* should focus on the isolation, standardization, and clinical evaluation of its bioactive compounds, especially mangiferin. Its fruits and other plant parts contain diverse bioactive compounds, including mangiferin, flavonoids, phenolics, and carotenoids, which exhibit antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and anticancer properties. Advanced studies are needed to confirm its therapeutic efficacy against chronic diseases such as against chronic diseases such as diabetes, cancer, and cardiovascular disorders. Emerging areas include nano-formulations, targeted drug delivery, and functional food development. Furthermore, the utilization of mango peels, seeds, and leaves for pharmaceutical, nutraceutical, and cosmetic applications, along with genomic and biotechnological improvements, offers significant potential for sustainable innovation. The growing scientific evidence highlights that *M. indica* may acts as a promising source for future drug discovery and development. With its favourable safety profile and broad therapeutic potential, continued research may further support its use in developing natural health products and innovative therapeutic agents.

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# Artificial Intelligence as the Future of Drug Discovery: Current Advances, Applications, Challenges, and Future Perspectives

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**Abstract**

Drug discovery is an expensive, time-consuming, and challenging process that spans over ten to fifteen years, with most compounds failing at different stages of drug development. There are serious obstacles and failures for the pharmaceutical industry while bringing new medicines to market. The use of artificial intelligence (AI) in drug discovery is growing exponentially. This technology is transforming the traditional drug design process into a data-driven one. AI can be used during multiple stages of the drug discovery process, such as target identification, molecule discovery, drug candidate optimisation, safety and efficacy prediction, drug repositioning, and companion diagnostics. However, various barriers to incorporating AI into pharmaceutical R&D, including data quality, model interpretability, ethical and regulatory concerns, and the need for experimental validation, must be addressed. The process of drug discovery and development will continue to depend on human expertise, even with the help of AI applications. Researchers should be aware of the opportunities and limitations of AI-driven drug discovery to harness its potential in pharmaceutical innovation.

***Keywords*:** Artificial Intelligence, Drug Discovery, Machine Learning, Virtual Screening, Drug Repurposing, Precision Medicine

## 1. Introduction

Drug discovery is a resource-demanding process that aims to develop, test and market new drugs. Drug discovery is a highly interdisciplinary field, and one of its challenges

is its long duration and high cost. This process is composed of multiple known stages including target identification, hit discovery, lead optimization, preclinical evaluations, clinical evaluations, and the approval of the drug by regulatory agencies. Current advancements in molecular biology, medicinal chemistry and pharmacology have improved the understanding of pathogenesis of diseases. The efficacy of drug discovery processes is proportionate to improvements made in the above-mentioned areas; drug discovery is still a tedious process. A new drug can take about 10-15 years to develop and cost about USD 2 billion, and most candidate drugs fail in preclinical and clinical evaluation stages. This is due to the drug not being therapeutically effective, the drug being toxic, the drug having poor pharmacokinetics and other biological considerations that are not known or anticipated [1, 2]. These challenges have created an urgent need for innovative strategies to accelerate drug development while reducing costs and improving success rates.

With the development of modern biotechnologies such as DNA sequencing, structural biology, and multi-omics, massive volumes of biomedical data have emerged. Databases including PubChem, ChEMBL, DrugBank, and PDB store data on millions of compounds, proteins, and drug targets, which underpins disease research and new drug development. However, processing large-scale and complex data is extremely difficult, and traditional methods such as molecular docking, pharmacophore modelling, QSAR, and molecular dynamics still have limitations.These methods often depend on fixed rules and manually selected features. As a result, they may not fully understand the complex and nonlinear relationships operating in biological systems [3].

Artificial Intelligence (AI) has reshaped drug discovery by helping scientists to analyze large and complex biological and chemical data. AI includes Machine Learning, Deep Learning, Natural Language Processing, Graph Neural Networks, and Generative AI. These methods can extract hidden patterns, make predictions, and improve with more data, supporting faster and better drug development [4].

Over the last decade, artificial intelligence has become deeply integrated into the drug discovery process. Machine learning enables researchers to identify disease-associated genes and potential drug targets. Deep learning algorithms now allow screening

hundreds of millions of compounds and predicting how they bind to target proteins. Moreover, QSAR-based AI can predict a drug's activity and absorption, distribution, metabolism, and toxicity, thus facilitating the elimination of undesirable compounds at an early stage. Recently, generative AI has been utilised to design molecules with desirable properties, enabling researchers to explore a much larger chemical space than traditional methods. This technological advancement has significantly accelerated the drug discovery process by identifying potential leads in a substantially shorter period than conventional approaches [4, 5].

One of the major successes of artificial intelligence in biomedical sciences is AlphaFold, a deep learning system that can predict the three-dimensional structure of a protein molecule with extraordinary accuracy. Since the structure of a protein is intimately linked to its function, determining the spatial arrangement of its constituent amino acids is critical to studying its biological role and developing therapeutics that can target it. Before AlphaFold, researchers used to thoroughly determine protein structures using tools such as X-ray crystallography, nuclear magnetic resonance (NMR) spectroscopy, and cryo–electron microscopy. AlphaFold's ability to perform this task on a scale of millions of proteins has extensively accelerated drug discovery and research by exploring their interactions with biological molecules [6, 7].

AI is useful not only for discovering new drugs but also for finding new uses for existing drugs and developing personalized treatments. During COVID-19, AI helped researchers identify possible antiviral drugs using genetic, chemical, and clinical data. AI can also group patients and identify biomarkers to choose treatments based on individual genetic information. These developments illustrate that AI is not merely accelerating the discovery of new drugs but is fundamentally reshaping the broader pharmaceutical research ecosystem [8].

Despite these impressive developments, there are still some challenges that must be overcome before AI can be widely adopted in drug discovery. Firstly, the success of such models critically depends on the amount and quality of data used to train them. Secondly, many AI models are "black-boxes" which makes their inner workings hard to understand and explains potential difficulties in interpreting the results. Data privacy and biases in algorithms, as well as reproducibility and regulatory hurdles,

present additional barriers to the widespread adoption of AI in drug development. Thus, while promising, AI should be used as an auxiliary to traditional methods and experimental research in pharmaceutical field, and not as a replacement [2].

. In view of the presented information, artificial intelligence (AI) can be considered as one of the most promising technologies for future drug discovery. The integration of computational intelligence into drug discovery processes and its combination with advances in cheminformatics, structural biology, systems pharmacology, and multi-omics research enables accelerating the development of therapeutics, reducing the costs of R&D, and increasing the overall success rates of drug discovery. This chapter discusses the progress in AI in drug discovery, provides an overview of the fundamentals of AI, covers its applications in drug discovery, and explores the opportunities and challenges of using AI for pharmaceutical research.

**2.Evolution of Drug Discovery and the Emergence of Artificial Intelligence**

The history of drug discovery is the history of humanity's experience, knowledge, science, and technology. In the last century, drug discovery transitioned from empirical and serendipitous art to target- and hypothesis-driven processes. Modern drug discovery is now an interdisciplinary field that integrates molecular biology, medicinal chemistry, computer science, and artificial intelligence to discover and optimize therapeutic candidates and molecules to hit and engage drug targets.

Drug discovery has evolved through distinct phases dominated by prevailing paradigms, approaches, and technologies of that era. Early natural history was guided by herbal remedies and traditional medicine such as Ayurveda, Traditional Chinese Medicine, and Egyptian medicine. Although herbal remedies were used to treat diseases, their modes of action and molecular mechanisms were poorly understood. In the 19th century, biologically active compounds isolated from natural sources such as morphine from *Papaver somniferum*, quinine from *Cinchona* bark, and salicylic acid from willow bark were discovered. This led to the foundation of medicinal chemistry and the target-based drug discovery era, which included the isolation and elucidation of numerous compounds with therapeutic activity [3].

The second half of the 20th century witnessed the advent of genomics and functional genomics and the development of powerful tools such as recombinant DNA

technology and high-throughput screening. Combined with an improved understanding of disease biology, these innovations emerged into target-based drug discovery (TDD), which is driven by rational design and uses genomics and proteomics to identify targets such as enzymes, receptors, ion channels, and nucleic acids. In parallel, high-throughput screening, combinatorial chemistry, and robotic technologies enabled rapid experimentation and identification of hits [2].

However, contemporary drug discovery remains costly, inefficient, and associated with long timelines with no guarantee of success. It may take over 10 years for a drug candidate to reach the clinic, while most drugs that enter clinical trials fail due to inferior efficacy, poor safety profiles, and unfavorable pharmacokinetics. According to Eroom's law, the number of new drugs discovered decreases exponentially with time while the cost of development increases inversely. These shortcomings have prompted the need for novel approaches and technologies to improve decision-making, streamline drug discovery, and reduce costs [10].

The genomic era is characterized by an explosion of biological and chemical data and the concomitant need to interrogate and mine these data to extract meaningful information to guide drug discovery. The Human Genome Project and next-generation sequencing ushered in a new era of molecular biology, structural biology, genomic and proteomic studies, and structural genomics. As a result, bioinformatic tools such as PubChem, ChEMBL, DrugBank, UniProtKnowledgebase, and Protein Data Bank have been developed to store and share genomic, proteomic and metabolomic data, and information on drug molecules. However, the need to analyze this deluge of data created new challenges. Consequently, in silico approaches such as molecular docking, quantitative structure–activity relationship (QSAR), pharmacophore modeling, and molecular dynamics have been developed to interrogate and analyze the data [3].

Artificial intelligence (AI) has revolutionized drug discovery by surpassing traditional computer algorithms that require explicit programming to carry out predefined tasks. AI and machine learning (ML) algorithms can automatically learn patterns from training data. Breakthroughs in computational hardware, cloud computing, GPU cores, and biomedical databases have enabled the development and deployment of

deep learning and graph neural networks, natural language processing, and generative AI to revolutionize drug discovery. These technologies reinforce hit and lead identification, virtual screening, ADMET profiling, target identification and validation, and drug repurposing [4].

A major turning point in the evolution of AI in drug discovery was the development of deep learning algorithms that could predict protein structure with high accuracy. AlphaFold by DeepMind was pivotal in accelerating research in structural genomics and biology by unveiling the secrets of protein folding and structure prediction. Similar breakthroughs are anticipated with AlphaFold 3 to further elucidate protein structure and interactions, with ramifications in structure-based drug design and discovery [6]. Similarly, generative AI can be used to design new molecules with desirable properties. Generative adversarial networks (GANs) enable the design of drugs with optimized potency, selectivity, ADMET profiles, and synthetic accessibility. Variational autoencoders, diffusion models, and transformer-based language models can also be leveraged to mine chemical space and discover new molecular entities with novel therapeutic indications [11]. These developments illustrate how AI can complement conventional drug discovery approaches to identify new opportunities for therapy.

At present, drug discovery is at the intersection of multi-omics, structural biology, cheminformatics, in-silico modeling, robotics, and AI to develop novel therapeutics. AI is transforming drug discovery from a hypothesis-driven paradigm to a data-driven approach that is more efficient and effective. In this new paradigm of drug discovery, AI is no longer an enabling technology but an integral part of the scientific process of generating biological insight, testing assumptions, making predictions, and accelerating the drug discovery and development process.

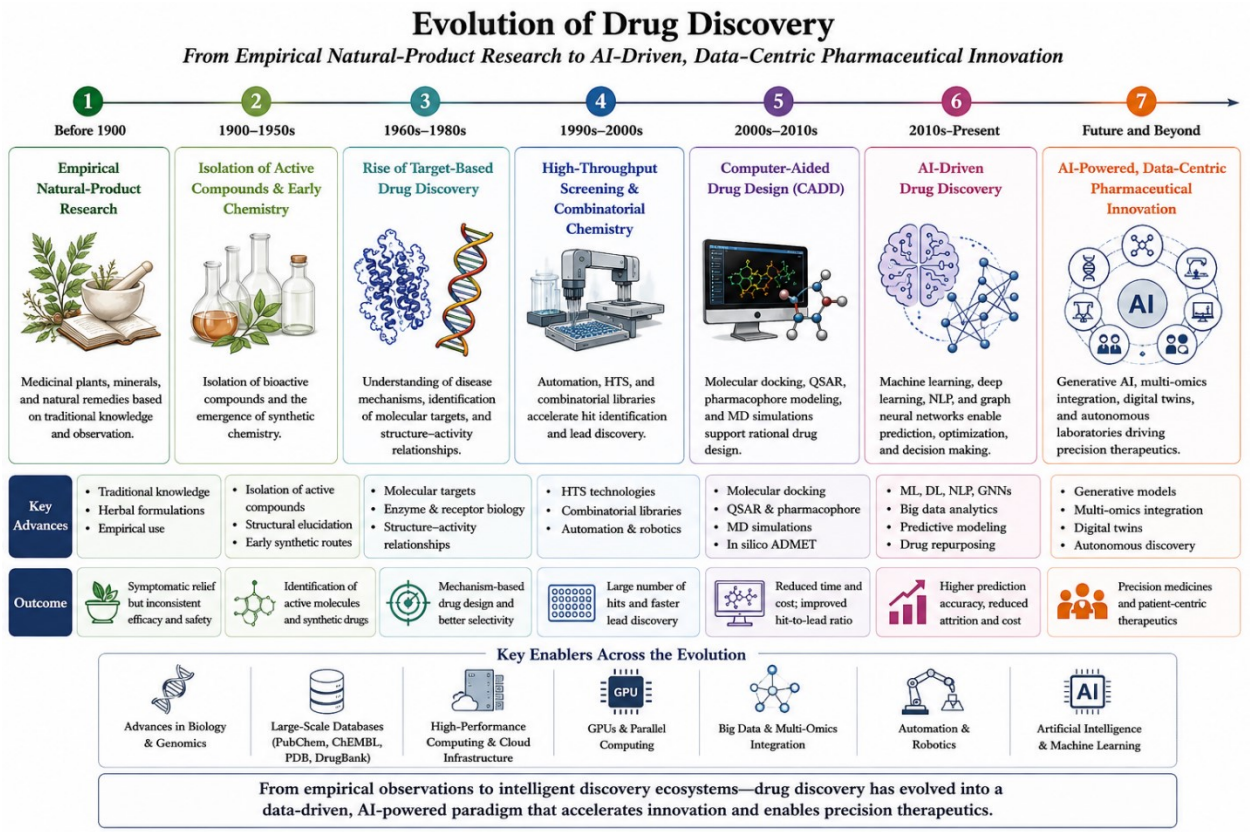



**Figure 1:** Evolution of drug discovery from empirical natural-product research to AI-driven, data-centric pharmaceutical innovation.

**Table 1.** Evolution of Drug Discovery Approaches: A Comparative Overview of Major Developmental Phases.

| Era | Predominant Approach | Key Technological Advances | Major Limitations |
|---|---|---|---|
| Before 1900 | Empirical medicine | Natural products, herbal remedies | Unknown mechanisms of action |
| 1900-1970 | Medicinal chemistry | Isolation of bioactive compounds, synthetic chemistry | Limited understanding of molecular targets |
| 1970-2000 | Target-based drug discovery | Molecular biology, recombinant DNA, HTS | High attrition and cost |
| 2000-2015 | Computer-aided drug discovery | Molecular docking, QSAR, MD simulation | Limited predictive capability |
| 2015-Present | AI-driven drug discovery | ML, DL, GNNs, AlphaFold, Generative AI | Data quality, interpretability, regulatory challenges |

## 3. Fundamentals of Artificial Intelligence in Drug Discovery

The exponential growth of biomedical data has made pharmaceutical discovery more data-intensive than ever before. The complexity of genomic, transcriptomic, proteomic, metabolomic, structural biology, and high-throughput screening data requires novel approaches for data exploration and mining. Artificial Intelligence (AI) has emerged as a powerful tool for analyzing massive and multidimensional data sets, allowing for unprecedented gains in critical analysis to support decision-making across the drug discovery lifecycle [10].

AI encompasses a broad range of computer algorithms that can perform tasks such as learning, pattern recognition, prediction, and decision-making. When it comes to drug discovery, AI is used as a decision-support system that works in tandem with research and development to prioritize potential drug candidates [4]

At the same time, there are other terms that fall under the umbrella of AI (Figure 2), including machine learning (ML). In drug discovery, supervised learning is applied to predict pharmacological properties, including molecular activity, toxicity, drug-target interactions, and pharmacokinetics. On the other hand, unsupervised learning is employed to discover hidden patterns and associations, and molecular clustering. Finally, reinforcement learning is utilized through reward systems in molecular design and optimization [2].

Moreover, deep learning (DL) is a subset of ML that has proven effective in drug discovery because of its capacity to encode features in a hierarchical manner using interconnected nodes in deep neural networks. Convolutional networks are particularly suitable for analyzing biomedical images and molecular structures, whereas recurrent networks and transformers are useful in encoding sequential data and molecular representations. Finally, graph neural networks (GNNs) enable the exploration of molecular graphs' properties, predicting ADMET profiles, and modeling drug-target interactions [12].

Natural language processing (NLP) is another important AI tool that allows for analyzing scientific literature, patents, clinical trial data, and electronic health records. Large language models (LLMs) contribute to literature mining and information

retrieval, facilitate knowledge discovery, and aid in report writing and hypothesis generation [13].

At the same time, generative AI is a powerful technology that can be leveraged to generate novel molecules, as opposed to simply analyzing existing ones. Variational autoencoders, generative adversarial networks, diffusion models, and molecular transformers can all be used for molecule design and optimization to modulate desirable properties such as activity, selectivity, pharmacokinetics, toxicity, and synthetic accessibility [11] [14]. Clearly, each of these techniques plays a critical role in accelerating pharmaceutical innovation and is likely to transform the industry in years to come.

**Table 2.** Comparison of Major Artificial Intelligence Techniques Used in Drug Discovery

| **AI Technique** | **Principle** | **Representative Applications** | **Major Advantages** | **Key Limitations** |
|---|---|---|---|---|
| Machine Learning | Learns predictive relationships from data | QSAR, ADMET prediction, activity prediction | Fast, interpretable, robust | Requires high-quality labelled data |
| Deep Learning | Multilayer neural networks | Virtual screening, docking, imaging | High predictive accuracy | Computationally intensive |
| Graph Neural Networks | Graph representation of molecules | Drug-target interaction, molecular property prediction | Preserves molecular topology | Large training datasets required |
| Natural Language Processing | Analysis of biomedical text | Literature mining, drug repurposing | Rapid knowledge extraction | Dependent on text quality |
| Generative AI | Designs novel molecular structures | De novo drug design | Explores new chemical space | Experimental validation required |

Despite these remarkable advances, AI models are not without limitations. Their predictive performance depends fundamentally on the quality, diversity, and completeness of the underlying datasets. In addition, many advanced deep learning models operate as black-box systems, providing highly accurate predictions while offering limited interpretability regarding the biological rationale underlying those predictions. To address this challenge, increasing attention has been directed toward Explainable Artificial Intelligence (XAI), which seeks to improve transparency by identifying the molecular features or biological variables that contribute most significantly to AI-generated decisions. Explainable models not only enhance scientific confidence but also facilitate regulatory acceptance and support the broader adoption of AI in pharmaceutical research.

Collectively, machine learning, deep learning, natural language processing, graph-based learning, and generative AI constitute the technological foundation of modern AI-driven drug discovery. Rather than functioning as independent computational approaches, these methodologies increasingly operate within integrated analytical frameworks that combine multi-omics data, structural biology, cheminformatics, and clinical information to support rational therapeutic development. As computational capabilities continue to advance, AI is expected to evolve from a supportive analytical tool into a central component of intelligent pharmaceutical research. The following section explores how these fundamental AI methodologies are applied across each stage of the drug discovery pipeline, from target identification to precision medicine.

## 4. Artificial Intelligence Across the Drug Discovery Pipeline

Artificial intelligence (AI) has transformed the traditional drug discovery paradigm by introducing data-driven approaches that improve efficiency, reduce costs, and accelerate decision-making throughout the pharmaceutical development process. Conventionally, drug discovery involves a sequential pipeline consisting of target identification, hit discovery, lead optimization, preclinical evaluation, clinical trials, and regulatory approval. This process is often associated with high attrition rates, prolonged timelines, and substantial financial investment. AI addresses these challenges by integrating computational intelligence with biological, chemical, and clinical data, enabling researchers to make more informed decisions at each stage of

drug development.[10] Rather than replacing experimental methods, AI complements laboratory research by prioritizing the most promising candidates for further investigation. Artificial intelligence contributes to nearly every stage of pharmaceutical research by integrating biological, chemical, and clinical information within a unified computational framework. Rather than functioning as isolated computational tools, AI technologies support decision-making from target identification to clinical development and post-marketing surveillance. As illustrated in Figure 2, AI enables a continuous and interconnected workflow that improves the efficiency, accuracy, and success rate of modern drug discovery.

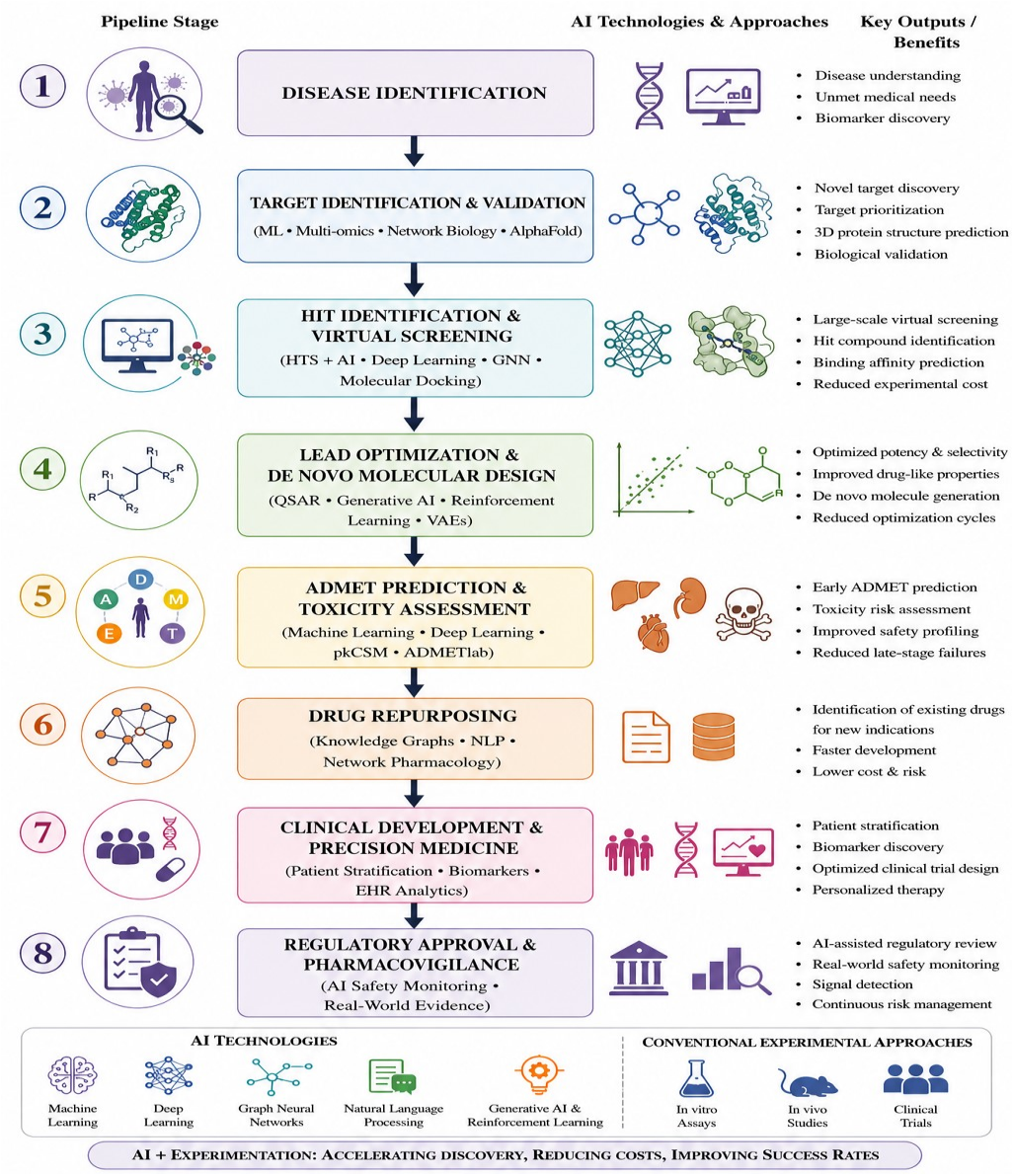



**Figure 2:** Integration of AI technologies across the major stages of the drug discovery pipeline

### 4.1 AI in Target Identification and Validation

Target identification is the first and one of the most critical steps in drug discovery because the success of a therapeutic intervention largely depends on selecting an appropriate biological target. Traditionally, target identification relied on experimental techniques such as gene expression analysis, proteomics, and biochemical assays. While effective, these methods are labor-intensive and often fail to capture the complexity of disease biology.

AI has significantly improved target identification by integrating multi-omics datasets, including genomics, transcriptomics, proteomics, metabolomics, and epigenomics. Machine learning algorithms analyze these large datasets to identify disease-associated genes, signaling pathways, and molecular networks that may serve as therapeutic targets. Network-based AI approaches further prioritize targets by examining protein-protein interactions and disease-gene associations, providing a systems-level understanding of disease mechanisms.[8]

A breakthrough in target validation has been the development of AlphaFold, which predicts three-dimensional protein structures with remarkable accuracy. Structural information generated by AlphaFold has expanded opportunities for structure-based drug design by enabling researchers to identify binding pockets and understand protein function, even for proteins lacking experimentally determined structures.[6] Consequently, AI has shortened the time required for target characterization and increased confidence in selecting biologically relevant targets.

### 4.2 AI in Hit Identification and Virtual Screening

Following target validation, the next objective is to identify compounds capable of interacting with the selected target. Traditionally, this stage relied on high-throughput screening (HTS), where hundreds of thousands of compounds were experimentally tested for biological activity. Although HTS has contributed to numerous successful drug discoveries, it is costly, time-consuming, and resource-intensive.

AI-powered virtual screening has emerged as an efficient alternative by computationally evaluating millions of compounds before laboratory testing. Machine learning models predict the biological activity of compounds using molecular

descriptors, chemical fingerprints, or graph-based representations, thereby reducing the number of compounds requiring experimental validation.

Deep learning models further enhance virtual screening by learning complex relationships between molecular structures and biological activity. AI-assisted molecular docking improves binding affinity prediction through advanced scoring functions capable of recognizing subtle protein-ligand interaction patterns. These approaches substantially reduce false-positive predictions while improving hit identification efficiency.[15]

Natural language processing also contributes by mining scientific publications, patents, and biomedical databases to identify previously reported compounds and therapeutic relationships. The integration of literature-derived knowledge with computational predictions enables researchers to prioritize compounds with greater confidence.

**4.3 AI in Lead Optimization**

After identifying promising hit compounds, medicinal chemists optimize their chemical structures to improve biological activity, selectivity, pharmacokinetic properties, and safety. Traditionally, lead optimization involves repeated cycles of chemical synthesis and biological testing, making it one of the most time-consuming phases of drug discovery.

AI has greatly accelerated lead optimization by predicting molecular properties before synthesis. Machine learning-based quantitative structure–activity relationship (QSAR) models estimate biological activity, lipophilicity, aqueous solubility, metabolic stability, permeability, and toxicity using historical experimental data. These predictive models allow researchers to prioritize compounds with desirable characteristics while minimizing costly experimental iterations.[16]

Recent advances in generative AI have introduced a paradigm shift in lead optimization. Instead of modifying existing compounds, generative models such as variational autoencoders (VAEs), generative adversarial networks (GANs), and diffusion models design entirely new molecular structures optimized for multiple objectives, including potency, selectivity, and synthetic accessibility. Reinforcement learning further enhances this process by iteratively improving molecular designs

based on predefined reward functions, enabling efficient exploration of vast chemical space.[17]

### 4.4 AI in ADMET Prediction

Poor absorption, unfavourable metabolism, toxicity, and inadequate pharmacokinetic behavior are among the leading causes of drug failure during clinical development. Therefore, early prediction of Absorption, Distribution, Metabolism, Excretion, and Toxicity (ADMET) properties has become a crucial component of modern drug discovery.

AI-based ADMET models predict key pharmacokinetic parameters such as gastrointestinal absorption, blood-brain barrier permeability, cytochrome P450 interactions, plasma protein binding, and renal clearance. Similarly, toxicity prediction models estimate hepatotoxicity, cardiotoxicity, mutagenicity, carcinogenicity, and other adverse effects before experimental evaluation.[18]

By identifying unsuitable compounds at an early stage, AI significantly reduces late-stage clinical failures and improves the overall efficiency of pharmaceutical research. Several publicly available platforms, including DeepPurpose, ADMETlab, pkCSM, and DeepTox, have demonstrated the practical value of AI-assisted ADMET prediction in contemporary drug discovery.[19]

### 4.5 AI in Drug Repurposing

Drug repurposing, also known as drug repositioning, involves identifying new therapeutic applications for approved or investigational drugs. Compared with de novo drug discovery, drug repurposing offers several advantages, including reduced development costs, shorter timelines, and lower safety risks because repurposed drugs often possess established pharmacokinetic and toxicological profiles.

AI has become a powerful tool for drug repurposing by integrating chemical structures, genomic data, disease signatures, protein interaction networks, and clinical records. Machine learning algorithms identify hidden associations between existing drugs and new disease indications, while natural language processing extracts evidence from biomedical literature and clinical reports.[20]

The importance of AI-assisted drug repurposing became particularly evident during the COVID-19 pandemic, when computational analyses rapidly prioritized existing

antiviral and anti-inflammatory drugs for further experimental and clinical evaluation. This demonstrated the ability of AI to accelerate therapeutic discovery during global health emergencies.[21]

### 4.6 AI in Clinical Development and Precision Medicine

The influence of AI goes beyond preclinical research. Its application to clinical and personalized medicine involves analyzing electronic medical records, genomic data, medical images, and smart devices to identify patients who may benefit from a certain drug or therapy. This helps find the target population for treatment, design clinical trials, and improve clinical outcomes.

Finally, AI is instrumental in enabling precision medicine that uses biomarker data alongside patient electronic medical records to determine the most appropriate treatment options. Instead of taking a one-size-fits-all approach to disease treatment, clinicians can use AI technology to personalize treatment and recommend drugs most likely to work for an individual patient based on their biomarker profile.[22]

Furthermore, utilizing pharmacovigilance powered by artificial intelligence enables the ongoing surveillance of post-marketing safety information to identify adverse events and ensure long-term drug safety.The role of artificial intelligence varies across different stages of the drug discovery pipeline and encompasses diverse machine learning approaches, extensive data mining, and varied applications. While employing machine learning and multi-omics approaches primarily enables target identification, deep learning and graph-driven techniques facilitate virtual screening and lead optimization, whereas utilizing AI for ADMET prediction, drug repurposing, and clinical assistance plays a major role in later stages of therapeutics development. In table 3 below, the main AI technologies, representative software, and applications in different stages of the drug discovery pipeline are presented.

**Table 3.** Comparison of AI technologies, representative computational tools and their applications across the major stages of the drug discovery pipeline

| **Drug Discovery Stage** | **Conventional Approach** | **AI Technologies** | **Representative Tools** | **Major Benefits** |
|---|---|---|---|---|
| Target Identification | Functional genomics, proteomics | ML, GNN, Multi-omics integration | AlphaFold, Open Targets | Improved target prioritization |
| Hit Identification | High-throughput screening | Deep Learning, Virtual Screening | AtomNet, DeepChem | Faster identification of bioactive compounds |
| Lead Optimization | Medicinal chemistry | QSAR, Generative AI, Reinforcement Learning | REINVENT, MolGPT | Enhanced potency and selectivity |
| ADMET Prediction | Experimental assays | ML, DL | pkCSM, ADMETlab, DeepPurpose | Early prediction of toxicity and pharmacokinetics |
| Drug Repurposing | Clinical observations | NLP, Knowledge Graphs | BenevolentAI | Reduced development time and cost |
| Clinical Development | Conventional clinical trials | ML, AI-driven EHR analysis | Tempus AI, Deep 6 AI | Optimized patient recruitment and precision medicine |

The successful implementation of AI in pharmaceutical research relies on multiple computational methodologies, each designed to address specific challenges within the drug discovery process. These techniques differ in their learning strategies, analytical capabilities, and practical applications, making them suitable for different stages of

therapeutic development. Table 4 summarizes the principal AI techniques currently employed in drug discovery and highlights their representative applications.

**Table 4.** Comparison of AI technologies, representative computational tools, and their applications across the major stages of the drug discovery pipeline

| **AI Technique** | **Drug Discovery Stage** | **Representative Application** |
|---|---|---|
| Machine Learning | Target identification | Disease-gene association, biomarker discovery |
| Deep Learning | Virtual screening | Protein-ligand interaction prediction |
| Graph Neural Networks | Hit discovery | Drug-target interaction prediction |
| QSAR Modeling | Lead optimization | Biological activity prediction |
| Generative AI | Molecular design | *De novo* drug generation |
| Reinforcement Learning | Lead optimization | Multi-objective molecular optimization |
| Natural Language Processing | Drug repurposing | Biomedical literature mining |
| Explainable AI | Model interpretation | Transparent decision support |
| Large Language Models | Knowledge integration | Literature synthesis and hypothesis generation |

### 4.7 Future Outlook of AI-Driven Drug Discovery

The future of drug discovery is envisioned to be driven by an integrated information platform that combines target discovery and development, *in silico* generation of small molecules, virtual screening, docking, molecular dynamics, ADMET prediction, and clinical decision-making. The future of drug discovery and development is anticipated to be empowered by such innovative technologies as autonomous labs, robotics, digital twins and multimodal foundation models. However, it is essential to recognize that AI is an enabling technology and should not replace experimental science; rather, it should be used in conjunction with the expertise of computational biology, medicinal chemistry, and pharmacology. The collaborative effort of humans and AI

has the potential to propel pharmaceutical R&D into an era of greater efficacy and safety, as well as usher in a new era of personalized medicine.

The promise of AI in drug discovery is evident in the number of pharmaceutical companies and academic institutions that are investing in these technologies, resulting in practical applications that harness the power of AI to identify drug targets, perform virtual screening of compound libraries, optimize lead compounds, discover new therapeutic uses for existing drugs and enable precision medicine. These practical applications confirm the value of AI in pharmaceutical R&D to find novel therapeutics and improve the drug discovery process.Table 5 summarizes representative case studies that highlight successful AI implementations across different stages of the drug discovery pipeline.

**Table 5.** Selected case studies highlighting the successful application of artificial intelligence across different stages of the drug discovery pipeline.

| Case Study | AI Technology | Application Stage | Key Achievement | Impact on Drug Discovery | Reference |
|---|---|---|---|---|---|
| AlphaFold (DeepMind) | Deep Learning | Target Identification and Validation | Predicted three-dimensional protein structures with near-experimental accuracy, enabling structural characterization of millions of proteins. | Accelerated structure-based drug design, target validation, and identification of ligand-binding sites, reducing dependence on experimental structure determination. | [6, 7] |
| INS018_055 (Insilico Medicine) | Generative AI, Deep Learning, Reinforcement Learning | Lead Optimization and *De Novo* Drug Design | AI-generated antifibrotic drug candidate designed through an integrated computational | Demonstrated that generative AI can substantially reduce drug design timelines | [23] |

| | | | | | |
|---|---|---|---|---|---|
| | | | workflow and advanced to clinical trials. | while simultaneously optimizing potency, selectivity, and pharmacokinetic properties. | |
| Baricitinib for COVID-19 (Benevolent AI) | Machine Learning, Knowledge Graphs, Natural Language Processing | Drug Repurposing | Identified baricitinib as a potential therapeutic agent for COVID-19 through AI-assisted analysis of biomedical knowledge networks. | Accelerated drug repurposing during the COVID-19 pandemic, highlighting AI's ability to rapidly identify new indications for existing drugs. | [24] |
| Precision Oncology (Tempus AI) | Machine Learning, Multi-omics Integration | Clinical Development and Precision Medicine | Integrated genomic sequencing, pathology, and electronic health records to support individualized cancer treatment. | Improved biomarker discovery, patient stratification, treatment selection, and clinical trial recruitment for precision oncology. | [25] |
| AtomNet (Atomwise) | Deep Learning | Virtual Screening | Applied deep convolutional neural networks to predict protein–ligand binding affinity and screen millions of compounds computationally. | Enhanced virtual screening accuracy and reduced the number of compounds requiring experimental validation, accelerating hit identification. | [26] |

| | | | | | |
|---|---|---|---|---|---|
| Exscientia AI Platform | Machine Learning, Generative AI | Lead Optimization | AI-assisted optimization of small-molecule drug candidates through iterative prediction of potency, selectivity, and ADMET properties. | Reduced medicinal chemistry cycles and accelerated progression of AI-designed drug candidates into clinical evaluation. | [1, 27] |

## 5. Challenges and Future Perspectives

Artificial intelligence (AI) is playing an increasingly important role in modern drug discovery by enhancing target discovery, enabling virtual compound screening, optimising candidate molecules, and repurposing existing drugs. Nevertheless, there are several scientific, technical, ethical, and regulatory challenges associated with the use of AI in pharmaceutical research, which significantly impact its effectiveness and practical implementation. The ability of AI to make accurate predictions in drug discovery is highly dependent on the quality of data and the accuracy of associated models, as well as the correctness of subsequent experiments. Thus, it is critical to identify and address these limitations to ensure the development of effective and safe pharmaceutical products using AI-driven methods [1, 2].

One of the biggest challenges is biomedical data. AI requires extensive data sets that are broad and properly annotated to allow for accurate predictions. There is an issue, however, with biological and chemical data sets in that they can be limited and inconsistent due to variances in testing and reporting procedures. Moreover, pharmaceutical companies may be reluctant to share data with competitors, and thus there are entire data sets that are unavailable to the public. As such, an AI trained on these data sets may make inaccurate predictions about therapeutics that it has not been trained on and have limited applications [2, 4].

Another significant limitation associated with the application of AI in drug design is the interpretability of its results. Deep learning algorithms typically operate as a “black box,” which means that their predictions are accurate but not transparent. Contemporary approaches to machine learning rarely disclose inner mechanisms,

which is unacceptable in pharmaceutical studies, where the importance of molecular insights cannot be replaced by any other consideration. Therefore, a considerable research effort has been devoted to developing explainable AI, which postulates the possibility of defining exactly which input variables affect model outputs. Such information is essential for validating the results obtained with the help of various machine learning techniques. The process of explainable AI helps scientists ensure that no steps have been overlooked, increasing the accuracy of calculations and supporting regulatory approval [28].

The experimental verification of AI predictions is another challenge for the current technology. While the AI system can prioritize the most promising drug candidates, computational biology cannot prove their effectiveness and safety. Every hypothesis suggested by the machine has to be tested in biochemical, cellular, animal, and clinical experiments. Therefore, one should consider AI as an intelligent assistant that helps researchers with some complex tasks while still being dependent on experimentation. The most effective way to use AI in drug discovery is to create a synergy between computational biologists, medicinal chemists, pharmacologists, structural biologists, and clinicians [1, 3].

The increasing application of artificial intelligence (AI) in healthcare poses critical ethical, legal, and regulatory challenges. For one thing, AI is typically trained on sensitive patient data, meaning that privacy, informed consent, and cybersecurity are of paramount importance. Additionally, there is a risk that algorithms will display prejudice if not tested and validated on sufficiently diverse data sets. At the same time, regulatory agencies are just beginning to formulate appropriate frameworks for the use of healthcare technologies. The FDA and EMA have started working on guidelines, but the field is still fraught with inconsistencies. As such, it is essential that pharma researchers embrace transparency, report biases, and continue monitoring the quality of AI-driven processes [2, 29]. Although artificial intelligence has demonstrated remarkable potential in transforming drug discovery, several scientific, technical, ethical, and regulatory challenges remain to be addressed before its widespread implementation in pharmaceutical research. Simultaneously, rapid advances in computational methodologies and data integration continue to create new

opportunities for AI-driven innovation. Table 6 summarizes the major challenges associated with AI in drug discovery together with emerging solutions and future research directions.

**Table 6.** Major Challenges and Emerging Future Directions in AI-Driven Drug Discovery.

| **Current Challenge** | **Impact on Drug Discovery** | **Emerging Solution/Future Direction** |
|---|---|---|
| Limited data quality | Reduced predictive accuracy | Standardized and FAIR biomedical databases |
| Black-box AI models | Poor interpretability | Explainable Artificial Intelligence (XAI) |
| Algorithmic bias | Limited model generalizability | Diverse and representative datasets |
| Regulatory uncertainty | Slow clinical adoption | Standardized AI regulatory frameworks |
| Experimental validation | High development costs | AI-guided autonomous laboratories |
| Computational complexity | Increased infrastructure requirements | Cloud and high-performance computing |
| Fragmented datasets | Poor knowledge integration | Multi-modal foundation models |
| Personalized treatment challenges | Variable therapeutic response | AI-driven precision medicine |

Despite the current limitations, the future of artificial intelligence appears bright, as the combination of various technologies including multi-omics, high-performance computing, structural biology, and cloud-based technologies may lead to an exponential growth in pharmaceutical advances. In the future, A.I.-driven drug discovery tools will employ integrative analyses of genomic, transcriptomic, proteomic, metabolomic, phenotypic, and clinical data to prioritize targets and develop personalized treatments [30].

One of the most promising developments in modern drug discovery is generative AI. Recent advances in transformer-based language models, diffusion models, and molecular foundation models enable the exploration of large chemical spaces and the discovery of molecules with desired properties, such as high potency, selectivity, favorable pharmacokinetics, low toxicity, and synthetic tractability. In contrast to traditional medicinal chemistry approaches, which are often limited to optimizing existing molecular scaffolds, generative AI can lead to fundamentally new discoveries by exploring regions of chemical space that were previously inaccessible. This has the potential to fundamentally change the way that drug discovery is performed by enabling researchers to identify novel target classes and develop first-in-class therapeutics [31].

Autonomous or self-driving laboratories are poised to become a significant innovation in the future of artificial intelligence driven drug discovery. By combining AI, robotic synthesis and testing in a closed-loop system, these systems allow for the rapid iteration and optimization of potential molecular structures. This has the potential to drastically reduce research timelines and increase efficiency in the discovery process.

The use of Large Language Models and multimodal AIs is likely to play an increasing role in pharmaceutical research by allowing these systems to access and analyze scientific literature, patents, databases and clinical data. The application of such AIs would likely be limited to assisting researchers in literature reviews, hypothesis generation, knowledge synthesis, and other similar tasks that require expert analysis of the scientific literature – but they should ideally be used as an additional tool rather than relied on exclusively.

AI-driven precision medicine is another area of pharmaceutical innovation that is likely to see significant investment in the future. By combining genomic, multi-omics, lifestyle, and clinical data, such systems could be used to identify and recommend individualized treatment procedures for individual patients. Digital twins can also be used to model disease progression and treatment response.

The future of AI-driven drug discovery will be defined by the availability of quality data, the development of reliable algorithms, ethical considerations, and rigorous testing and validation procedures. While the field promises to accelerate the drug

discovery process and make it more efficient, AI is likely to function as an intelligence amplifier rather than a standalone system capable of replacing human researchers.

## 6. Conclusion

Artificial intelligence (AI) is set to revolutionize drug discovery by enabling faster and more efficient research processes. By harnessing the power of AI in combination with molecular biology, cheminformatics, structural biology, and multi-omics, it is possible to enhance target identification, virtual screening of compounds, drug optimization, and prediction of pharmacokinetics and toxicology. These advances promise to shorten, streamline, and reduce the resource burden of the drug discovery pipeline.

Nevertheless, it is important to note that AI is not a substitute for empirical research. The predictive accuracy of AI models is only as good as the data used to train them, and there are also barriers to validation such as non-transparent algorithms, data biases, ethical concerns, and regulatory challenges. Accordingly, while AI is a powerful tool, its findings should be interpreted with caution and subjected to rigorous laboratory and clinical evaluation before concluding a final result.

Various future advances in AI, such as the development of more sophisticated and interpretable algorithms, leveraging the potential of generative AI, multimodal approaches, autonomous labs, digital twinning, and precision medicine, may contribute to accelerating drug discovery. Ultimately, the future of drug discovery will be governed by the collaborative synergy between artificial intelligence and human expertise in deciphering the mechanisms of disease and developing extraordinary therapeutic interventions.

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# Millets as Future Crops: Bridging Traditional Knowledge, Sustainability and Policy Intervention

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**Abstract-** Nutri-cereals, or millets, are widely grown in tropical and subtropical regions of the world. Millets holds profound cultural significance and have the ability to mitigate malnutrition and food deprivation. In terms of global agricultural production, it ranks as one of the sixth crops. The grain and plant are among the oldest traditional staple food crops and are less prone to pest damage and illness. Millet's nutritional value is similar to that of major crops since they are rich in protein, carbohydrates, dietary fiber, vitamins, minerals, and phytochemicals. Bioactive substances such tannins, flavonoids, lignins, trypsin, and others are plentiful in millets. Millets are a superior option for health-conscious people due to their low glycemic index. Millets provides defense against oxidative stress and long-term conditions like cancer, heart disease, and neurological diseases. There are several culinary uses for millets, including value-added products that enhance cuisine. The UN proclaimed 2023 to be "the International Year of Millets" following the intervention. Government- Led Programs have a considerable influence on millet's production, research, and development in order to assimilate them into important food systems in the future. They are a strong contender for food availability and sustainable agriculture due to their versatility and durability.

**Keywords:** Nutri-cereals, malnutrition, neurological disease, sustainable,versatility .

## INTRODUCTION

According to Muskan *et al*. (2025), millets are classified as small-seeded grains that have been cultivated in tropical and subtropical locations for over thousands of years. The Latin word "milum," which denotes grains, is where the word "millet" originates. The *Poaceae* family of plants includes a variety of small-seeded species. The crops

are vital to the ecological and economic security of the country and are widely grown for human consumption. These grains are highlighting deep cultural value and many times feature in folklore and cultural stories Tripathi and Vyas, 2023. Additionally, they play a major role in Indian Ayurvedic and Chinese medicine for treating digestive complaints and insomnia Muskan *et al*., 2025.

In India they are considered indigenous staple foods, especially in the rural parts; people are very fond of them. Millets are grown traditionally in the rain-fed and sometimes in the dry environments of the Deccan Plateau of southern India. Millets also have an early germination period and a life expectancy of 60 days, making them ideal for the regions where other crops succumb to stress Tripathi and Vyas, 2023.

**Types of Millets-**

Depending on the size of the grains, millets can be categorized as major or minor millet. The smaller millets are Kodo, barnyard, proso, tiny, foxtail, brown top millet, fonio, and teff, whereas the major millets are sorghum, finger millet, and pearl millet.

After harvesting and cleaning, major millets can be eaten right away, but minor millets need to be processed first to gently remove the antioxidant-rich outer layers of the grain Jacob *et al*., 2024.

**Nutritional profile of Millets-**

The nutritious composition of millets makes it stand out among cereals. They are an excellent source of carbohydrates; the main component of carbs in grains is starch, which improves digestion and regulates the glycemic index. Proso and foxtail millets have the highest protein content among millets, with other kinds ranging from 6 to 13. Pearl millet has the highest fat content among millets, which range from 2 to 8. Numerous secondary metabolites, such as flavonoids, tannins, and phenolic compounds, are rich in vitamin B complex and function as antioxidants Jacob *et al*., 2024.

Millets are nutrient-dense grains that include minerals (2–4), dietary fiber (12–20), protein fat (1.5–5), and a variety of other phytochemicals Bhatt *et al*., 2022.

According to Ambati and Sucharitha, K.V. (2019), they are also a rich supply of essential amino acids, with the exception of lysine and threonine. On the other hand, sulfur-containing amino acids like methionine and cysteine are rather abundant in them.

**Millets-derived bioactive compounds-**

Alongside legumes, millets are frequently eaten for their better amino acid profile, increased protein digestibility, and protein supply. They are a great source of bioactive chemicals and abundant in micronutrients. Among the significant bioactive substances found in millets are flavonoids, tannins, lignins, phytates, beta-glucan, and trypsin inhibitors.

In order to treat and lessen the effects of chronic illness, certain substances are essential. In addition to their direct physiological effects, millet-derived bioactive chemicals have an indirect effect on the composition of the gut microbiota, which is crucial for identifying and preventing chronic diseases. Previous studies have proven that adding millets to day-to-day life is effective in lowering the circulating lipopolysaccharides (LPS) Muskan *et al*., 2025.

**Health promoting properties of Millets-**

According to Ambati and Sucharitha K.V. (2019), millets are gluten-free; they can help control weight, lower the risk of genetic celiac disease, and lessen obesity. Millets have been shown to be a good source of tannins, phytates, and phenolic acid, which are anti-nutrients and lower the incidence of breast and colon cancer. Alpha-glucosidase and pancreatic amylase levels were lowered by millets, which decreased the incidence of diabetes-related cataract disease. They are rich in magnesium, making them beneficial for heart patients. The phytochemicals present in millets help to lower cholesterol and prevent cardiovascular disease. Mishra *et al*., 2012.

Pearl millets lessen the incidence of gallstones, while finger millet and small millet increase hemoglobin concentration, lowering the risk of anemia. All things considered, millets are the center of necessary nutrients that are crucial for controlling

lifestyle illnesses, making them a significant component of human well-being Muskan *et a*l., 2025.

**Environmental Benefits of Millets-**

Because of their many benefits, including their usage as food, feed, and value-added products, millets are frequently referred to as "miracle crops." These benefits significantly contribute to agrodiversity. Millets require minimal nutrient inputs and have the ability to prevent erosion. As compared to other cereals, millets tolerate high temperatures; these old crops are durable and resistant to biological and environmental stresses. It was studied that these nutri-rich crops require 70% more water efficiency than rice and can thrive across a wide temperature range as high as 42%. These crops can be ideal for the tropical countries, as they can thrive in high temperatures and are named as “the last crop that stands against drought” Kheya*et al.,* 2023.

Millets could be a reliable alternative to wheat, especially in regions with acidic soil. Throughout their development and growing season, millets need relatively little water. Since millets can sequester more carbon dioxide from the atmosphere and transform it into oxygen, they are categorized as C4 plants, which have been demonstrated to be more environmentally friendly Kumar *et a*l., 2018. Compared to rice and wheat, millets perform photosynthesis 50% more effectively Pandey and Bolia, 2023. Photosynthetic capacity is higher in millets and enhances dry matter accumulation, making them an ideal crop for climate-adaptive cropping systems Muskan *et al*., 2025.

**Production Status of Millets-**

Globally, 718 lakh hectares of land are used for millet crop cultivation, with 138 lakh hectares located in India alone. In 2022, a total of 304.8 lakh metric tons were produced, of which 120 lakh metric tons came from India. India produces a diverse variety of millets that may be grown in a variety of agroclimatic conditions, and it leads the globe in production with 39%, followed by Nigeria with 11% and China with 9% Sharma *et al*., 2025.

More than 93 countries are engaged in the production of millets, yet only seven have more than a million hectares of millet land, with developing nations accounting for more than 97% of the total. According to the USDA's 2016–17 data report, Africa and Asia account for roughly 96.89% of the world's millet production, which is projected to be 27,572,961 tonnes. With a total output of about 514,248 tonnes, the European Union ranks second with 1.81%, and the United States ranks third with 1.18% with 335,698 tonnes. The Australian subcontinent's nations, on the other hand, only produce 36,112 tons, or 0.127 percent of the world's total production. Half of the world's millet is derived from pearl millet, which is accompained by foxtail, proso, and finger millet Bhatt *et al*., 2022.

With 20 agroclimatic zones and 157.35 million hectares of land under cultivation, India has the second-highest percentage of agricultural land worldwide. A Department of Agriculture Cooperation and Farmers Welfare report states that for the 2017–18 crop year, India is anticipated to produce 279.51 million tonnes of food grain Nelson *et al*., 2019. India is the leading producer of millets, and twenty-one states are engaged in millet production. The top leading states of India are Maharashtra, Karnataka, and Rajasthan. In India, the area devoted to millet cultivation is 13.63 million hectares, yielding 18.02 million tonnes at 1256 kg/ha Singh *et al*., 2023.

**Integrating millets into modern lifestyles**:

1 **Product innovation –** Several innovations were made to improve the nutritional profile and palatability of food. The conversion of source material into cooked or useful forms was created with the aid of processing techniques. These processed foods have better taste, texture, nutrition, and shelf life. Additionally, the anti-nutritional elements are sometimes reduced by processing technology Saleem *et al*., 2023. They are used to make gluten-free value-added items like bread and porridge, snacks, noodles, and biscuits Rasika A. *et al.,* 2024.

2 **Pharmaceutical applications-** Numerous studies have shown how important millets are for health. In mice, the protein derived from millets has positive effects,

especially in preventing metabolic disorders, hyperglycemia, cardiovascular disease, liver damage, and intestinal problems. Millet peptides and proteins, whether derived from natural or enzymatic sources, are powerful nutraceutical constituents with bioactive qualities like antiviral or antibacterial characteristics, making them beneficial supplements for newborns to fight malnutrition Sikdar *et* al., 2025.

3 **Research and Monitoring-**Numerous breeding projects and the development of genetic resources have made it possible to address food security and sustainability in a changing environment. For sorghum, a number of pan-genomes have been created, adding to the collection of assembled genomes and sequencing data. In breeding programs, evaluating genetic diversity is essential for enhancing germplasm Kasule *et al*., 2024.

**Government Policy and Initiatives-**

**1-International Year of Millets 2023-**With the backing of 72 additional countries, the United Nations General Assembly officially declared 2023 to be the International Year of Millets (IYOM). The Indian government enthusiastically suggested and commemorated 2023 as IYOM. Awareness campaigns are used to spread awareness about the advantages of millets as food and the acceptability of value-added products both domestically and internationally Rasika A *et a*l., 2024.

According to Gireesh *et a*l., (2025 NITI Aayog), the national government has taken massive initiative to promote millet cultivation and mainstream millet diets across India.

2-**National Millet Mission (NMM)-** Initiated by the Indian government in 2007, this program aims to produce and consume millets. The primary goals of the mission are to strengthen the value chain, help farmers, teach them about smart agriculture, and improve the lives of small farmers.

**3-Adoption of millets into the Public Distribution System (PDS) -**The program's goal is to give those living below the poverty line access to reasonably priced, wholesome food. People can get millets at reduced prices thanks to the program.

**4-Minimum Support Price (MSP)-**Designed to support them monetarily and protect them from exploitation. It helps the farmer to depend on the package and helps them sustainably grow their millet production activities.

**5-Millet Experience Center (MEC**)-The Ministry of Agriculture and Farmers Welfare (MoA&FW), in coordination with the National Agricultural Cooperative Marketing Federation (NAFED), established a center in 2023 whose aim is to provide information about millets and their health benefits as well as promote the consumer-ready products of millets in the marketplace.

**6-The Initiative for Nutritional Security through Intensive Millets Promotion (INSIMP)-** It was implemented in 2017 by the Ministry of Agriculture and Farmer Welfare, which was funded by Rashtriya Krishi Vikas Yojana (RKVY). The aim of the initiative is to develop the technology of foxtail millet by raising the productivity of the backward districts.

**Conclusion**

The nutritional composition, health benefits, role in sustainable agriculture, and present national and international standing of millets all contribute significantly to nutritional security. When compared to main grains, millet is falling behind due to inadequate infrastructure, a lack of awareness, and market constraints. However, millets received considerable recognition following the year of millets and government backing.

In an environment when food and water crises are imminent, millets can be a crucial food for meeting the objectives of food and nutritional security Wang and colleagues, 2018. Although millets improve nutritional security and have a smaller environmental impact, in some situations they can take the place of staple crops. Growing them alongside these staple crops may provide a number of advantages. Because these grains grow well in marginal areas, they help promote more environmentally friendly and sustainable farming methods. Millet cultivation is significantly helpful in

achieving the goal of SDG; however, numerous bottlenecks associated with the millet supply chain are still hampering its mass consumption Pandey and Bolia, 2023.

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# Health and Crop Losses Due to Aerosol-Induced Air Pollution in the Indo-Gangetic Plains

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**Abstract:** The Indo-Gangetic Plains (IGP) are a hotspot for aerosol-induced air pollution, driven by industrial activities, vehicular emissions, biomass burning and natural dust transport. This study examines the dual impact of aerosol pollution on human health and agricultural productivity in this densely populated and agriculturally critical region. High aerosol concentrations degrade air quality, leading to respiratory and cardiovascular diseases among the local population. Simultaneously, aerosols alter climatic conditions by scattering and absorbing sunlight, reducing solar radiation essential for crop photosynthesis and yield. Seasonal activities such as crop residue burning exacerbate these impacts, contributing to spikes in aerosol levels. This research quantifies the health and economic losses due to aerosol exposure and evaluates mitigation strategies, including clean energy adoption and sustainable agricultural practices. The findings emphasize the need for integrated policies addressing air quality, public health, and agricultural resilience to enhance sustainability in the IGP.

**Keywords:** Aerosols, Air Pollution, Indo-Gangetic Plains (IGP), Agriculture, Biomass Burning, Health Impacts, Climate Change

**Introduction:** Atmospheric aerosols, similar to hydrosols, are defined as particles in solid / liquid / mixed phase that are dispersed in the atmosphere [1]. Their sizes range from $\sim 10^{-3}$ to $10^{2}\,\mu m$ and number concentrations range by over 4 orders of magnitudes depending on location, from few particles over poles to more than $10^{4}$ particles over tropical climates.Atmospheric aerosols come from natural and anthropogenic sources, with natural sources like sea spray and biomass burning contributing more than anthropogenic sources like industrial processes and transportation. Regional variations in pollution can significantly alter this ratio,

especially in industrialized northern hemispheres [2]. Aerosols play important role in altering the radiation budget of the earth-atmosphere system at local, regional and global scale. They scatter and absorb visible wavelength of incoming solar spectra, directly, apart from modifying the cloud droplet size distribution, thereby changing the lifetime of clouds as well as its radiative properties [3,4,5].

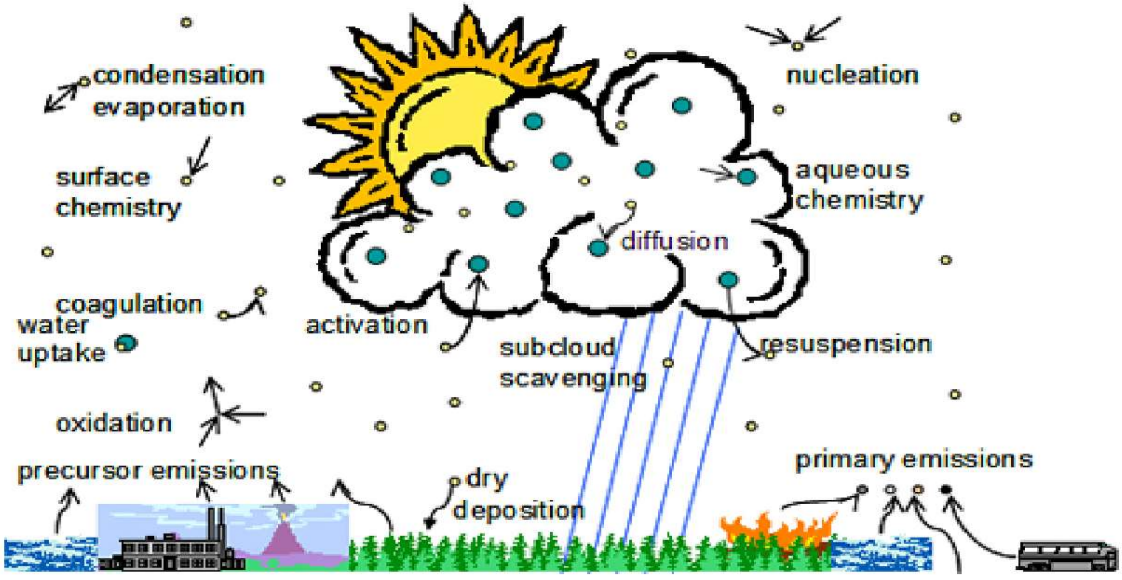



Figure 1:Various sources and sinks of aerosols (http://www.phys.unsw.edu.au/RESEARCH/ATMOSPHERIC/atmospheric_research.html).

Indo-Gangetic Plain is the largest, heavily populated (around 1/7 of the world's population) region of the globe, recognized as a **hotspot of aerosol pollution**, driven by a combination of natural and anthropogenic factors. This densely populated region experiences high levels of fine particulate matter (PM2.5 and PM10) and other aerosols, resulting from activities such as agriculture, industry, and urbanization. It encompasses ~610,000 km² polluted as well as fertile agriculture basin in the northern India [6]. The region is bordered by most of northern and eastern India heavily populated parts of Pakistan, the parts of southern Nepal and nearly all of Bangladesh. The region is named after the Indus and the Ganga, the twin river systems that exhaust it. Large cities of the Indo- Gangetic Plain are Karachi Hyderabad, Multan, Islamabad, Rawalpindi, Faisalabad, Lahore (All in Pakistan), Amritsar, Bathinda, Ludhiyan,

Chandigarh, Delhi, Jaipur, Kanpur, Lucknow, Allahabad, Varanasi, Patna, Kolkata (All in India) and Dhaka, Bangladesh. IGP is bounded by Himalayas on the norths, which feed its numerous rivers and are the source of the fertile alluvium deposited across the region by the two river systems while the southern edge of the plain is marked by the Vindhya- and Satpura Range, and the Chota Nagpur Plateau in south, southwest and southeast azimuth. IGP suffers with foggy, hazy, and smoggy conditions during winters, which are largely due to population enhancement and increasing urbanization/industrialization [7]. On the other hand, it provides approving climate for the agricultural activities due to its fertile soils and abundant water supply from the southwest monsoon and the rivers originating from the Himalayan glaciers such as the Ganges. Therefore, the cultivable land forms a major fraction of the total geographical area in the IGP region (~76%) as compared to the rest of India (~50%) (http://dacnet.nic.in/). IGP has distinct topography; therefore, this region can be summarized as a type of region, where, both anthropogenic and natural, aerosols show different seasonal characteristics and mixing capabilities. General seasonal abundance shows that the winter months are dominated by the fine-mode aerosols, formed by various anthropogenic sources from the IGP region (Srivastava et al. 2011b), and pre-monsoon or summer months are occupied by the coarse-mode mineral dust, primarily from the Thar Desert region in the western Rajasthan and its frequent transportation over the IGP region [8, 9].

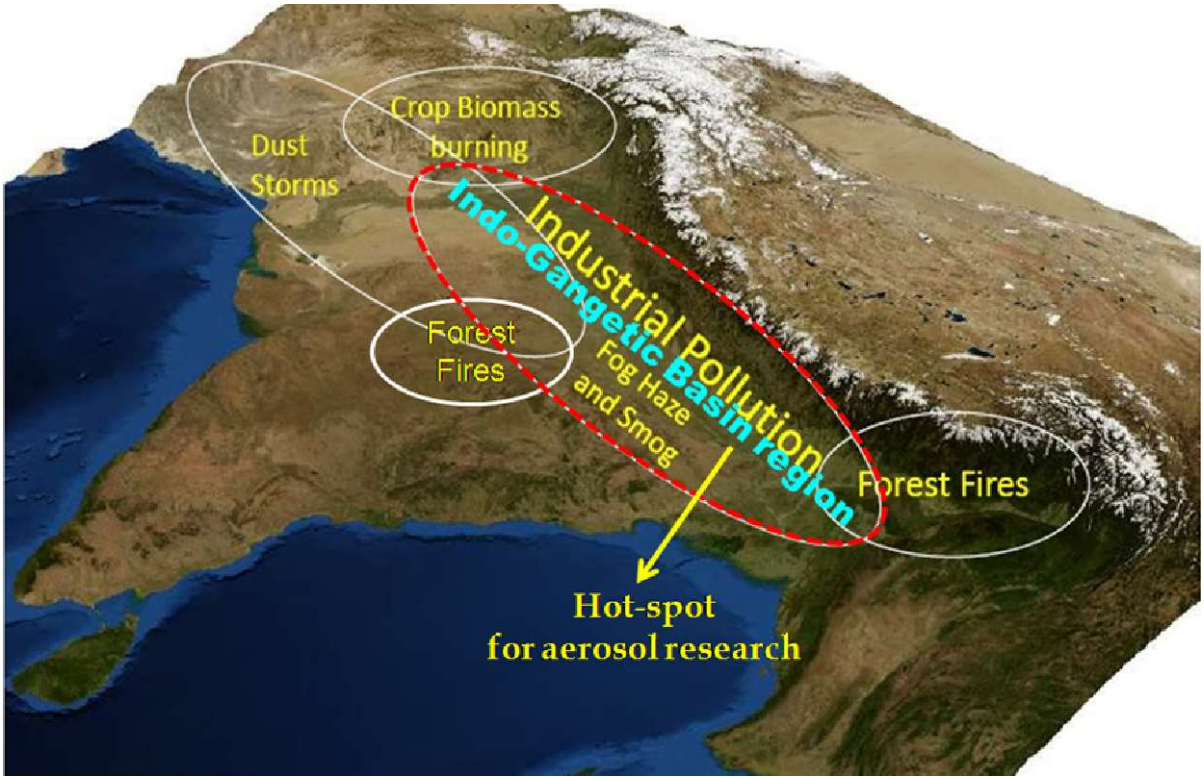



Figure 2: IGP region, showing unique topography surrounded by the variety of aerosol emission sources (Adopted after alteration from personal presentation of William K. M. Lau on Aerosol Monsoon Rainfall Variability and Climate Change).

With rising population and industrialization, the IGP region is a major source region for aerosols, where different aerosol species such as mineral dust, soot, nitrate, sulphate particles and organics are formed and transported to this region.IGP contains both rural and urban population and various kinds of emission sources including natural and anthropogenic. In rural areas, bio-fuels burning, such as wood, dung cake and crop waste, mainly contribute to the major aerosols loading, whereas in urban areas, aerosol emissions from fossil fuels burning, such as coal, petrol and diesel oil dominate. IGP is also dominated by absorbing aerosol emissions (black carbon and inorganic oxidized matter is observed, which is mostly fly ash from coal-based power plants and particles from open burning of crop waste/forest-fires over the IGP whereas the dust emissions from the Thar Desert affect the region, predominantly during the pre-monsoon months. The seasonal influence of emissions from the forest-fires and open burning of crop waste from the central India were also found over IGP as biomass aerosol contribution.

**Impact on Agriculture Due to Aerosol-Induced Air Pollution in the Indo-Gangetic Plains:** The Indo-Gangetic Plains (IGP) are a critical agricultural hub, producing a substantial portion of South Asia's staple crops such as wheat, rice, and maize. However, aerosol-induced air pollution poses significant challenges to agricultural productivity in the region. The effects of aerosols on agriculture are complex and multifaceted, affecting crop growth, soil quality, and overall food security.

I. **Reduction in Photosynthetically Active Radiation (PAR)**: Aerosols scatter and absorb sunlight, reducing the availability of PAR essential for photosynthesis. This process, termed "solar dimming," directly limits crop growth and reduces yields. Aerosols such as black carbon and sulphates scatter sunlight, causing diffuse radiation, while others absorb it, reducing the overall light intensity that plants can utilize. The reduction in PAR decreases the efficiency of photosynthesis, particularly during key growth stages like tillering and grain filling in crops such as wheat and rice. In the Indo-Gangetic Plains, where aerosol concentrations are among the highest globally, solar dimming has been linked to a measurable reduction in crop yields, particularly during the winter growing season. Research indicates that wheat and rice yields in the Indo-Gangetic Plains are reduced by approximately 10–20% due to diminished sunlight availability caused by aerosols [10]. The economic implications are profound, with losses running into hundreds of millions annually, affecting farmer livelihoods and food security.

II. **Wheat and Rice Production Challenges**: Recent research using the **Agricultural Production System Simulator (APSIM)** model has highlighted the detrimental impact of anthropogenic aerosols on wheat production in the eastern Indo-Gangetic Plains (IGP). Wheat grain yields are reduced by **11.2–13.5%** due to aerosol-induced effects on sunlight and climate conditions. The total biomass production showed even more substantial reductions, estimated at **21.2–22%**, indicating significant losses in the overall growth of the wheat plants. Aerosols negatively affect evapotranspiration (ET), reducing it by **13.5–**

**15%**. This decrease can alter plant water use and overall crop water productivity, compounding stress during critical growth phases.



Figure 3:Aerosols from Biomass burning

Wheat, as a winter crop in the Indo-Gangetic Plains (IGP), exhibits high sensitivity to aerosol-induced climatic changes, particularly cooling effects. Aerosols reduce the intensity and availability of sunlight and modify temperature and precipitation patterns, leading to significant disruptions in wheat cultivation. Aerosol-induced cooling prolongs the monsoon season in some areas, delaying the drying of fields and consequently the sowing of wheat. Late sowing shortens the crop's growth period, particularly during the critical grain-filling phase. Due to delayed sowing and reduced sunlight (solar dimming), wheat grain yields in the IGP are estimated to decrease by 10–20%, depending on aerosol concentrations in the atmosphere [11].

III. **Impacts on Maize and other crops:** Aerosols contribute to elevated levels of ground-level ozone, a potent phytotoxic pollutant. Ozone penetrates plant stomata, causing oxidative damage to cells, reducing leaf function, and impairing growth. Aerosol-induced changes in regional temperature and precipitation patterns disrupt planting and growth schedules. These delays

shorten the growing season, particularly for rain-fed crops like maize. Maize yields are observed to decrease by approximately **10-15%** due to light limitation and ozone damage in high-aerosol regions of the IGP. Pulses, oilseeds and vegetables are similarly affected, showing reduced productivity due to impaired photosynthesis and stress-related damage.

**Key Health Impacts of Aerosol Air Pollution:** Aerosol air pollution has a profound impact on human health [11], particularly in regions like the Indo-Gangetic Plains (IGP), where pollution levels are among the highest in the world. These impacts are largely due to fine particulate matter (PM2.5), black carbon, and other pollutants that are suspended in the air, penetrating deep into the lungs and bloodstream.

**Respiratory Diseases**: (I). **Chronic Respiratory Conditions**: Long-term exposure to aerosol pollutants, especially PM2.5, is strongly linked to the development of chronic respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD), and bronchitis. These fine particles can irritate the airways and cause inflammation, reducing lung function over time.

(II). **Increased Mortality**: Studies indicate that exposure to particulate matter increases mortality rates from respiratory diseases. According to the World Health Organization (WHO), air pollution is one of the leading causes of death globally, contributing to millions of premature deaths annually.

**Cardiovascular Effects:** (I).**Heart Disease**: Fine particulate matter and black carbon contribute to cardiovascular diseases by triggering inflammation in the arteries and disrupting normal blood flow. Studies show a significant increase in heart attacks, strokes, and other cardiovascular events due to exposure to high levels of air pollution.

(II). **Blood Pressure and Heart Function**: Long-term exposure to air pollution can also affect heart function, leading to higher blood pressure and increased stress on the heart. People with pre-existing heart conditions are particularly vulnerable [10].

**Premature Births and Developmental Effects:** Exposure to air pollutants, especially in regions with high aerosol levels, has been linked to an increased risk of premature births, low birth weight, and developmental issues in infants. The pollutants may

interfere with fatal development by reducing the oxygen supply to the baby and causing inflammation.

**Cancer Risks:** Prolonged exposure to particulate matter and other carcinogenic components of aerosol pollution increases the risk of lung cancer. The International Agency for Research on Cancer (IARC) has classified air pollution as a Group 1 carcinogen.

**Premature Deaths:** A report by the Global Burden of Disease study found that outdoor air pollution was responsible for an estimated 4.2 million premature deaths globally, with a significant proportion of these deaths occurring in South Asia, particularly in the IGP.

**Conclusion:**

In conclusion, aerosol-induced air pollution presents a dual threat to the Indo-Gangetic Plains (IGP), a region crucial for both human health and agriculture. The health impacts include an increase in respiratory diseases, cardiovascular issues, and premature deaths, particularly among vulnerable populations. This is mainly due to fine particulate matter (PM2.5) and ozone exposure, both of which have been shown to severely compromise respiratory function and overall health. Additionally, agricultural productivity in the IGP is also suffering due to reduced sunlight from aerosol scattering, which impairs photosynthesis and leads to lower crop yields, particularly for staple crops like wheat, rice, and maize. Wheat yields, for example, have been reduced by up to 20% due to delayed sowing, stunted growth, and crop evapotranspiration issues driven by aerosol pollution. To mitigate these risks, coordinated efforts are crucial. Reducing emissions from agricultural burning, industrial sources, and vehicular traffic will help reduce aerosol concentrations. Additionally, investing in healthcare infrastructure to manage the rise in pollution-related diseases and adopting sustainable agricultural practices—such as crop varieties resistant to pollutants—will safeguard both public health and food security in the IGP. These strategies are essential for mitigating the harmful effects of aerosol pollution and ensuring the long-term well-being and productivity of the region.

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# Gamma Radiation-Mediated Stress Responses and Climate Resilience in Plants

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**Abstract**

As climate instability amplifies environmental stresses are continuously lower crop yields through severe abiotic stress. Due to the impact of ionizing radiation, like gamma rays, which has prominent role in altering plant lifecycle, it is critical abiotic stressor that disrupts cellular functions with complex metabolic processes and gene expression. Gamma radiation has dual role in plants, which act as both as an abiotic stressor and as a tool for enhancing stress tolerance. Exposure to high doses of gamma radiation creates oxidative stress over formation of reactive oxygen species (ROS), that damages cellular components, and severe mutation in DNA.

However, the low and controlled dose of radiation can stimulate adaptive responses by activating antioxidant, stress related proteins, phytohormones and by accumulating protective metabolites to protect plant under several abiotic stresses. The response of Gamma radiation improved tolerance against several abiotic stress like, drought, salinity, and heat stress by enhancing various defense response including, osmotic adjustment, photosynthetic efficiency, and expression of stress-related genes. Along with that gamma radiation has contribution in mutation breeding programs for the development of improved crop varieties with desirable agronomic traits that adapt in harsh conditions. This chapter describes the molecular mechanisms of gamma radiation including, its role in climate-related stress tolerance, hormetic responses, and

applications in mutation breeding. Understanding the dual role of gamma radiation is important for developing climate-resilient crops varieties which enhance productivity and sustains in adverse environmental circumstances.

**Keywords**: mutation, gamma radiation, abiotic stress, DNA, antioxidants

## Introduction

Increasing climatic anomalies increase the occurrence of abiotic stress by disrupting ecological balance, that enhances the ecological concern. Abiotic stress is persistent challenge to plants that can disturb their yield by altering cellular response. Several abiotic conditions are threats to agricultural system and cause stress includes drought, salinity, extreme temperature condition, heavy metal contamination in soil and radiations (Zhang *et al.,*2022). Among these stresses radiations affect plants biological and metabolic processes that impact its health, particularly, the ionizing radiations like gamma radiations which alters the growth and development by several physiological, and molecular pathways (Ali *et al.,*2015; Adrovic, 2012).

Gamma rays are regarded to be more intense electromagnetic radiation that contain more penetrating power than alpha and beta particles, with energies ranging from 10 to several hundred kilovolts of electron (Zhong *et al.,*2021) It is measured in Gray (Gy) units, (1 J/kg) which, means the assimilation of one joule of energy per kilogram of plant tissue (1 J/kg) (Kovacs & Keresztes, 2002).

Ionizing radiations including Gamma rays are instantly disrupt plant cellular compounds by interacting with water, atoms, and molecules to produce free radicals. (Kovacs & Keresztes, 2002).

Interestingly, the gamma radiation has a dual role in plants, it acts as both abiotic stressor and have crucial role in stress mitigation as shown in (figure 1.). In recent years, mutation breeding studies required gamma radiation to develop new and improved crop varieties which increases tolerance to various abiotic environmental stresses and better agronomic traits. Along with that it is important to understand how plant respond to gamma radiations mediated abiotic stress. This chapter discusses the

dual role of gamma radiation in creating abiotic stress and its role in different abiotic stress conditions.

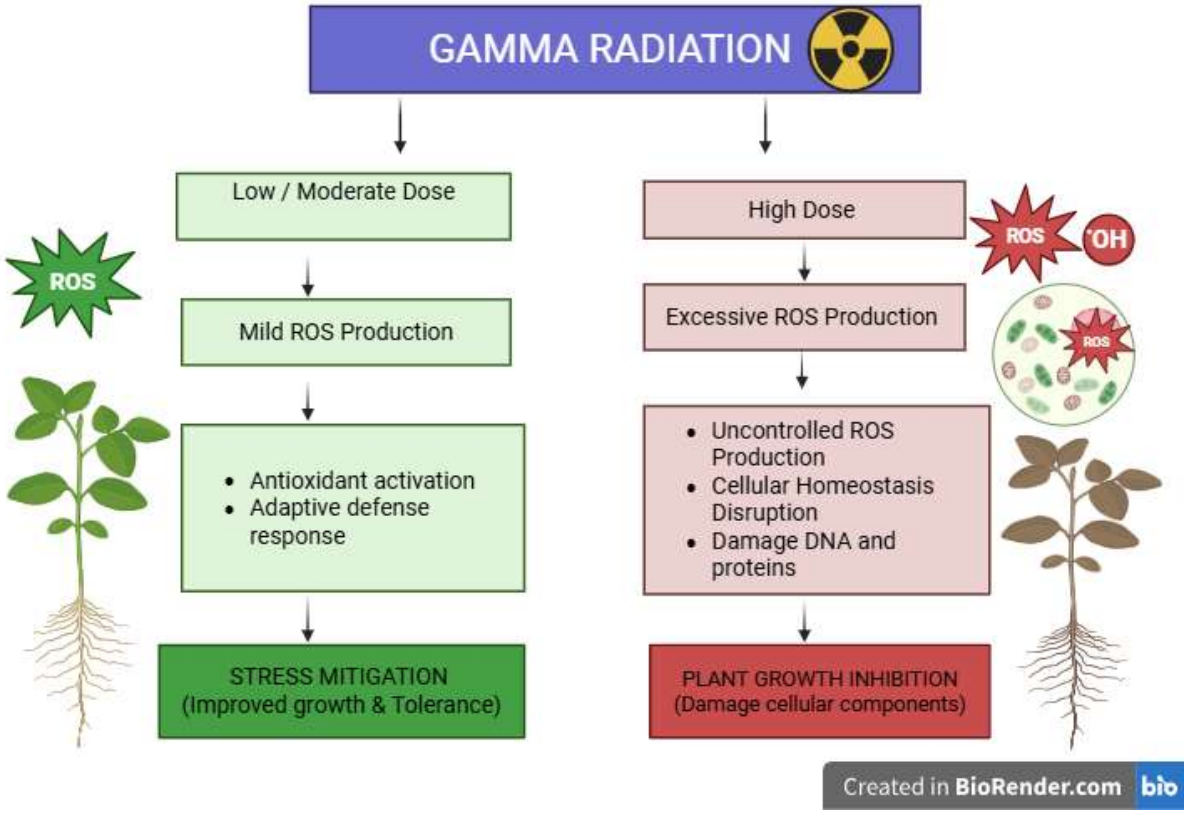



Figure 1. Dose-Dependent Effects of Gamma Radiation in Plants Created in https://BioRender.com

1. **Molecular and Cellular Mechanisms of Gamma Radiation Perception and Signaling**

When plants were exposed with higher dose of gamma radiation, they perceived through the excessive generation of reactive oxygen species (ROS) which caused redox imbalance inside the cell. The water molecules undergo radiolysis, which produces highly reactive radicals like hydroxyl radicals (•OH) and hydrogen peroxide ($H_2O_2$) which harms cellular components however, these molecules also function as important signaling molecules that starts stress-responsive pathways (van de Walle *et al.,*2016; Sachdev *et al.,*2021). As the level of ROS increases it trigger a cascade of intracellular signaling response which further activates protective genes responsible for defense mechanism and increase accumulation of protective secondary metabolites (Sachdev *et al.,*2021;Kim, 2025).

Stress signalling pathways also increases the formation of phytohormone like abscisic acid (ABA) which, increases the activity of NADPH oxidase and control the production of $H_2O_2$ (Qi *et al.,*2014; Kim, 2025). ABA-mediated stress signalling prevents the transpiration losses by closing stomata that gives ability to plants for survive in harsh environments (Qi *et al.,*2014; Katiyar *et al.,*2022). Also, the excessive concentration of ROS damages cellular components, but in moderate concentration they act as secondary messengers which promotes the activation of antioxidant enzymes to maintain cellular redox homeostasis (Zhang *et al.,*2016; Katiyar *et al.,*2022).

Stress related transcription factors such as WRKY, NAC, and bZIP are activated by ROS- and ABA-mediated signalling networks, that enables the plants to coordinate stress adaptation (Jan *et al.,*2012; Ligterink& Hirt, 2001; Kim *et al.,*2011). These transcription factors control the expression of genes associated with stress adaptation by osmotic balance along with, antioxidant defense enzymes activations and cellular protection. Both ROS signaling and ABA-mediated responses, are protective mechanism of plants to survive under radiation stress (Kim *et al.,*2011; Wang *et al.,*2022).

Gamma radiation affects the accumulation of several stress-responsive metabolites, including γ-aminobutyric acid (GABA), methylglyoxal (MG), and β-alanine, that aid in plant adaptation under radiation stress (Pishenin*et al.,*2021). GABA helps in energy production and nitrogen metabolism during stress (Bouche, & Fromm 2004). Along with that, methylglyoxal facilitates signalling response by ROS, Ca2+, and ABA-mediated pathway. Its lower concentrations help in adaptive tolerance response, while the high dose creates oxidative stress (Kaur *et al.,*2016; Pishenin*et al.,*2021). Another non-proteinogenic amino acid, β-alanine, helps in the synthesis of coenzyme A and secondary metabolism to promote radiation-induced hormetic responses (Parthasarathy *et al.,*2019; Pishenin*et al.,*2021).

Radiation stress creates severe genomic injury in plants by double stranded DNA break that affect cell cycle and loss of chromosomal arm, with lethal mutation which affect plant health. Plant starts DNA repair mechanism to adapt in ionizing radiation

stress by cell cycle checkpoint that aids in activation DNA repair pathways (Gill *et al.,*2015). Some DNA repair genes like RAD51, BRCA1, ATM, ATR, and ERCC1, are involved in identifying and repairing DNA damage caused by ionizing radiation (Hefner *et al.,*2003; Donà *et al.,*2013;Szurman-Zubrzycka*et al.,*2023).

## 2. Antioxidant Defense and Metabolic Adjustments under Gamma Radiation

Plants initiate response to oxidative stress caused by gamma radiation, to combat and survive by activating critical antioxidant defense responses. The massive influx of ROS signals in plant stimulates the production of protective compatible solutes, or osmolytes, like proline, soluble sugars, polyamines, and glycine betaine to safeguards cellular structures in stress. In these stressful conditions, the presence of osmoprotectant and cryoprotectant like proline, aids in scavenging of hydroxyl radicals (•OH) and singlet oxygen ($^1O_2$), to reduce oxidative damage (Qi *et al.,*2014; Katiyar *et al.,*2022). Apart from that it stabilizes cellular components by providing osmotic strength to cytosol, vacuole and the external environment. It sustains energy metabolism by maintaining the level of NADP+/NADPH in stress circumstances (Abo-Hamad *et al.,*2013; Liang *et al.,*2013; Katiyar *et al.,*2022).

Stress activates the coordinated mechanism using several antioxidants to survival in adverse condition by multiple enzymatic and nonenzymatic pathways using enzymes like Superoxide Dismutase, Catalase, Peroxidase, Ascorbate Peroxidase, Glutathione Reductase, ascorbic acid and glutathione which contain specific mechanisms to detoxify ROS and give tolerance ability to plants (Das & Roychoudhury, 2014; Geng *et al.,*2019). Along with this response plants accumulate phenolic and flavonoid content to stabilize cellular environment for example, in different medicinal plants the presence of ROS increase in activity of phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS) to increase flavonoid content for radiation protection (Vardhan *et al.,*2017).

## 3. Role of Gamma Radiation in Tolerance to Climate-Related Stresses

As the climatic conditions are constantly changing it give rise to multiple abiotic stresses which makes crops highly vulnerable to stress conditions and effect plant

health by altering several developmental, structural and metabolic functions. These condition leads to drought, salinity, and extreme temperatures stresses that is heavily responsible for decline of global yield. Using biotechnological approaches like priming plants with controlled, low-dose gamma irradiation can regulate metabolic and genetic functions, that enhances the plant tolerance to these climate changing challenges.

### 3.1 Drought Stress Tolerance by Gamma Radiation

Drought condition arises due to prolonged water deficits circumstances which initiates a series of physiological and biochemical disruptions, due to moisture deprivation that restricts seed germination, vegetative growth is affected due to the loss of turgor pressure and structural cellular collapse (Anjum *et al.,*2021). Metabolically, water scarcity imbalance the cellular water content, that forces stomatal closure for reducing transpiration water loss (Hasanuzzaman*et al.,*2013). The restriction of internal carbon dioxide concentration affects the light and dark reactions of photosynthesis, The metabolic disruption causes an overproduction of reactive oxygen species (ROS), which disturb cellular organelles (Seleiman*et al.,*2021; Farooq *et al.,*2009). When the plants are exposed with lower dose of gamma radiation it alters the expression of stress-responsive transcription factors like DREB2 and ERF, which regulates drought adaptation pathways, so the gamma treatment contributes to crop resilience by upregulating protective gene for stress signaling to activate plant adaptation response (Ma *et al.,*2024; Dossa *et al.,*2016; Al-Sayed *et al.,*2025). Gamma treatment also promotes the accumulation of proline and soluble sugars, which maintain cellular hydration and membrane stability during drought stress Also, it increases chlorophyll content, to enhance photosynthetic efficiency, and root function that allows better water uptake and energy production. For instance, in soybean (*Glycine max*), seed pre-treatment with 20 Gy gamma rays improved drought tolerance by improving its defense mechanisms and reducing its yield loss under water deficit conditions (Moussa, 2011).

### 3.2 Salinity Tolerance by gamma radiation

Ionic toxicity and imbalance create saline environment for plants which affects its growth by, osmotic stress in plants that leads to saline toxicity, this toxicity deforms roots physiology, which disrupt the nutrient uptake, with reduced photosynthesis efficiency that affect cellular metabolism in plant. Saline condition affect plant morphologically by showing several stress symptoms like damaging its leaves and root morphology (Carillo *et al.,*2011; Shahid *et al.,*2020). To protect the salinity stress when plants were treated with controlled gamma irradiation it increases salinity tolerance which help plants in reducing oxidative damage under saline conditions. For example, in triticale plants pre-exposure of seeds to gamma radiation at an optimized dose of 63 Gy increases stress tolerance under 150 mM NaCl conditions by increasing antioxidant activity and reducing oxidative stress markers like hydrogen peroxide and malondialdehyde, which improved physiological and biochemical performance (Atghaei*et al.,*2023). Similarly, gamma irradiation increases chlorophyll content and cellular stability, for plant resilience under salt stress conditions by effective seed priming techniques that are used to cope stress challenges (Beyaz, 2020). The low dose gamma radiation can promote adaptive responses that help plants in maintaining growth and productivity in salinity stress conditions (Katiyar *et al.,*2022).

### 3.3 Gamma Radiation and Heat Stress Tolerance

Heat stress arises when plant experience high temperature severely affects plant growth by disrupting important physiological processes like photosynthesis, stomatal conductance, alters water uptake efficiency, antioxidant activity that decreases yield and growth of plant (Ali *et al.,*2020). Heat stress degrades photosynthetic protein and dissociated D1 and D2 protein and chloroplast associated signalling that alters genes responsible for adaptive response in stress (Zahra *et al.,*2023).

The low intensity of gamma irradiation support plant to tolerate high temperature conditions by activating several protective physiological and molecular responses, like in *Arabidopsis thaliana*, pre-exposure of low-dose gamma rays prevent from heat stress tolerance by activating antioxidant defense systems and reducing oxidative damage under elevated temperature conditions (Zhang *et al.,*2016). Gamma irradiation

helps in accumulation of heat shock proteins to protect cellular proteins like mitochondrial (HSPs 22), which is molecular chaperones that maintain the stability of tomato cells during heat stress (Banzet *et al.,*1998; Berka *et al.,*2022). Its exposure to grapevine cultivars increases sprouting, plant height also increases phenolic, flavonoid content and their antioxidant activities (Ud-Din *et al.,*2025).

## 4. Gamma Radiation Effects in Different Crops

Depending on the radiation intensity length of exposure, and type of plant species, gamma radiation causes several physiological, biochemical, and molecular responses in plants table no. 1 explains the effect of gamma radiation s in different crops (Jan *et al.,*2012).

| **Type of Crop** | **Gamma radiation effect** | **References** |
|---|---|---|
| Rice (*Oryza sativa*) | Gamma radiation increases oxidative stress markers that decrease photosynthetic efficiency, growth, and reproductive capacity in plant, the acute exposure causes immediate physiological damage, while chronic exposure leads to long-term reproductive failure | (Choi *et al.,* 2021). |
| *Arabidopsis thaliana* | Gamma radiation induced ROS production is also dose-dependent which altered the expression of various antioxidant and signal transduction genes, like catalase, ferritin, and WRKY transcription factors | (Kim *et al.,* 2011). |
| Soybean (*Glycine max*) | The increased doses of gamma radiation reduce plant height, biomass, and chlorophyll content, while the activities of antioxidant enzymes superoxide dismutase and peroxidase are suppressed that causes cellular damage and affect stress tolerance mechanism of plant | (Alikamanoglu *et al.,*2011) |
| *Lemna minor* | Gamma exposure also reduces plant growth and alters antioxidant defense mechanism at higher radiation doses and it changes in ploidy level for adaptive genomic responses under prolonged radiotoxic conditions | (Van Hoeck *et al.,*2015). |

**Table no. 1 Effect of gamma radiation s in different crops**

## 5. Hormesis in Plants under gamma radiation stress

When plant experience mild concentration of stress it, safeguards itself and start tolerance mechanism by inducing a series of several biochemical and physiological pathways, this mechanism is hormesis that enhances plant development under stress condition (Siemieniuk*et al.,*2025). In this context, several scientists describe the phenomenon of hormesis that occurs when low intensity of gamma radiation enters in plants, to cope stress they activate stress responsive proteins and increase phenolic and flavonoids compounds in plants (Ostrovskaya *et al.,*2022; Miller & Miller, 1987). These components contribute to stress adaptation by maintaining cellular homeostasis and improving tolerance mechanisms. But the excessive radiation exposure leads to cellular dysfunction and genomic alterations (Gill *et al.,*2015; Ali *et al.,*2015).

## 6. Gamma radiation in mutational breeding

Gamma radiation is used in mutational breeding in plants that depends on selecting of appropriate radiation dose, as the response varies with plant species, tissue type, developmental stage (Alvarez *et al.,*2019). Radiopriming and mutation thresholds are measured using $LD_{50}$ (median lethal dose) or $GR_{50}$ (median growth reduction dose) that describe the exact intensity needed to activates helpful genetic variations for plant adaptation (Datta & Silva, 2026; Riviello-Flores *et al.,*2022). Low doses of gamma radiation increase plant growth, regeneration, and beneficial for biochemical changes, whereas high doses can inhibit growth, reduce regenerative capacity, and damage tissue (Al-Safadi *et al.,*2000). The higher radiation has huge impact on genetic level, the mutation alters DNA sequences that severely affects chromosomes and these defects inherited to the next generation of plants (Ma *et al.,*2021; Chakravarty & Sen, 2001). Therefore, determining the appropriate dose is an important for mutation breeding to balance beneficial genetic variation with plant survival in radiation stress (Riviello-Flores *et al.,*2022). Globally, many improved crop varieties have been developed yet, using induced mutagenesis studies.

## 7. Challenges and Limitations of Gamma Radiation usage

Although the application of Gamma radiation contains several benefits but they also contain some challenges.

- Analysing optimum dose of radiation are important before application due to the variation in intensity of radiation which varies among different species which affect the different stage of plant, dose can't be optimum for all species it can be harmful to other species (Ergun *et al.,*2023; Ghasemi-Solokluie*t al.,*2023).
- High intensity of gamma radiation creates chromosomal abnormalities, due to lethal mutation which disrupts the DNA sequence and affect several developmental stages and reproductive capacity (Nurmansyah*et al.,*2018; Ghasemi-Solokluie*t al.,*2023).
- Induced mutations are either harmful or agriculturally insignificant (Brock, 1971; Mba, 2013).
- In mutation breeding studies making the selection of desirable mutants is a tedious and time taking process (Chaudhary *et al.,*2019).

Several environmental factors influence the effectiveness of radiation treatments under field conditions. Therefore, researchers need a careful dose optimization and detailed analysis of plant responses are essential before using in large quantity agricultural studies.

## 8. Conclusion and future prospectives

Gamma radiation has complex and dual role in plants stress studies that influence its structural, biochemical, and genetic responses. Depending on the dose, it can function either disruptive abiotic stressor or stimulant for stress recovery that enhance plant tolerance under adverse environmental conditions. Through the regulation of antioxidant capacity, phytohormonal signalling, and stress related genes gamma radiation contributes to the development of desirable climate-resilient varieties in plants.

Besides its positive consequences gamma radiation show hormetic responses, where mild radiation exposure stimulates structural, physiological and genetic responses for stress adaptation. But excessive intensity causes severe damage. Along with that, gamma radiation are most effective physical mutagens that is used in mutation breeding studies for generating genetic variability and developing improved crop varieties having desirable agronomic traits. Despite these benefits, there are some challenges also like identifying optimum dose with its species-specific responses, undesirable mutations, and the time required for mutant selection continue to limit their broader usage.

Future studies are required to understand the molecular response of radiation-induced stress adaptation by using advanced approaches. The integration of gamma radiation-based mutagenesis with modern breeding studies and genome editing techniques may accelerate the development of climate-resilient crop varieties.

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# Environmental Literacy as a Tool for Mitigating Health Risks from Emerging Contaminants

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## Abstract

Emerging contaminants such as microplastics, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS), novel industrial byproducts, are becoming a serious threat to both human health and the environment. These substances are found in water, soil, and food, and can cause serious health problems, including hormonal changes, immune issues, and some types of cancer. Traditional methods like regulation and technology are helpful but not enough to solve this growing problem. This paper explains how environmental literacy (EL), especially environmental health literacy (EHL), can help people, communities and organizations to understand these risks and take action to protect themselves. The main findings are: (1) Emerging contaminants produce multiple system health effects in the body and often require precautionary and community-based solutions. (2) Environmental health literacy (EHL) strengthens adaptive behaviors, encourages collective action, and supports the use of effective risk-reduction methods. (3) Coordinated strategies combining formal education, clear and customized communication, public participation in research (citizen science) and policy engagement offers the greatest likelihood of reducing exposures and harm. Overall, improving environmental literacy can turn knowledge into action and help create healthier and more sustainable communities.

**Keywords:** Emerging contaminants, environmental literacy, Health risks, policy, awareness.

## Introduction

Emerging contaminants are chemical or particulate agents such as pharmaceuticals, personal care products, microplastics, and per- and polyfluoroalkyl substances (PFAS) are newly recognized in the ecosystem that has raised new challenges for environment and human health (Boxall et al., 2012; Fenton et al., 2020). Emerging contaminants are characterized by their novelty, often complexand incomplete toxicological understanding, complex exposure pathways (water, food, air, soil), unregulated, potential to bioaccumulate and produce subtle chronic health effects at low concentration (Wee et al., 2023; Finn & O'Fallon, 2018). Research associates these contaminants with endocrine disruption, immune dysfunction, reproductive issues,

and even cancer, emphasizing the urgent need for coordinated strategies to reduce their impact (Boahen, 2025; Fenton et al., 2020).

Environmental literacy (EL) and environmental health literacy (EHL) are essential for empowering individuals and communities to understand, respond to, and mitigate environmental risks. Although advancements in monitoring and remediation have improved risk management, many people still lack the necessary knowledge and skills to limit exposure or push for broader change. EL provides the foundation for understanding environmental processes and making informed decisions, while EHL specifically connects this understanding directly to human health impacts (Matos et al., 2025; Buta et al., 2025). Together, they empower individuals and communities to adopt safer practices, monitor environmental conditions, and promote stronger policy reforms. Enhancing EHL also strengthens community resilience, especially in vulnerable areas facing pollution and poor infrastructure. Thus, developing environmental and health literacy is not just an educational objective but a vital public health strategy that supports scientific and regulatory efforts to address emerging contaminants and protect both environment and human well-being.

This chapter investigates the role of environmental literacy as a powerful approach to mitigate health risks posed by emerging contaminants. It analyzes current knowledge about these contaminants and their effects on human health, reviews evidence connecting literacy with behavior that minimizes risk, and suggests a practical framework for incorporating EHL into environmental management and public health programs. Ultimately, the study highlights that strengthening environmental literacy through education, effective communication, and community participation can turn awareness into meaningful action, promoting healthier and more sustainable communities.

**Emerging Contaminants**

Emerging contaminants are chemicals or biological agents that are newly recognized or newly problematic due to expanded use. They are not routinely tracked in the environment but may pose risks to human health and ecosystems. The main Categories of Emerging Contaminants are:

- **Pharmaceuticals and personal care products (PPCPs):** Prescription and over-the-counter medicines, insect repellents, antibiotics, painkillers (ibuprofen, diclofenac), hormones, cosmetics, sunscreen agents that enter water systems through excretion and improper disposal. These substances can cause biological effects on wildlife and may also impact humans through long-term, low-level exposure (Wydro et al., 2024)

- **Per- and polyfluoroalkyl substances (PFAS):** These are the broad group of synthetic chemicals valued for their resistance to water, oil, and stain-resistant properties widely used in products like firefighting foams, non-stick cookware, and textiles. Some PFAS are known to persist in the environment, bioaccumulative and are associated with various adverse health outcomes (Kwiatkowski et al., 2020; Coperchini et., al 2020).
- **Endocrine-disrupting chemicals (EDCs):** These include substances such as specific plasticizers, bisphenols, and certain pesticides that can interfere with hormonal systems, even at very low concentration specially during critical stages of growth and development (Sauvé & Desrosiers, 2014).
- **Micro- and nano-plastics (MNPs):** Small plastic particles typically smaller than 5 millimeters (microplastics) and 100 nanometers (nanoplastics) that originate from degradation of larger plastic materials. They a may carry chemical additives or sorbed pollutants that can persist in the environment, enter food chains, and potentially causeadverse effects on human health and ecosystems (Uthra et al., 2023).
- **Industrial Chemicals and Solvents**: Industrial chemicals and solvents such as flame retardants (PBDEs), surfactants, and plasticizers are extensively used in electronics, textiles, and manufacturing industries. These compounds often persist in the environment,leading to contamination of air, water, and soil. They can disrupt ecosystems, cause toxicity in aquatic life, and may cause long-term health problems in humans (Maddela et al., 2022).
- **Antibiotic-resistant genes (ARGs) and microbes**: It develop mainly from the excessive use of antibiotics in medical and agriculture. These resistant organisms survive antibiotic treatment and can transfer resistance traits through genetic exchange. Their widespread occurrence in the environment poses significant global health concern by reducing the antibiotics effectiveness against infectious disease(Niu et al., 2022).
- **Nanomaterials**: It Includes silver nanoparticles, titanium dioxide, and carbon nanotubes, are extensively use in electronics, cosmetics, and medicine due to their unique properties.Because of their nanoscale size, they easily interact with organisms and ecosystems. Their environmental persistence,and uncertain biological effects raise growing concerns about potential environmental and health hazards.

## 2. Mechanisms of harm and public health concerns

Emerging contaminants (ECs) can harm human health through multiple mechanisms, including endocrine disruption, suppression of immune function, cancer development,

reproductive and developmental problems, metabolic disorders, and neurotoxicity (Lei et al., 2015; Chen et al., 2023; Gore et al., 2015). People may be exposed to these substances by ingestion of contaminated water, food, inhaling airborne particulates, or through dermal contact with consumer products and occupational routes (Sauvé et al., 2014; Wang et al., 2024). A major concern is chronic low-dose exposures to these contaminants throughout life, which can combine with other stress factors such as poor nutrition or infections to produce complex health issues (Ullah et al., 2022; Gore et al., 2015).

For many ECs, epidemiological evidence is still limited, making it difficult to determine safe exposure levels or set clear regulatory standards (Lei et., al 2015)

**Environmental Literacy and Environmental Health Literacy**

**Environmental literacy (EL)**: Environmental literacy (EL) broadly refers to the knowledge, skills, and motivation to understand the environment and make responsible choices about it. It includes factual knowledge about ecosystems and pollution, thinking scientifically, taking part in community actions, and showing positive attitudes and behaviors toward protecting the environment (McBride et., al 2013)

**Environmental health literacy (EHL)**

It is a specialized area that connects the environment with human health. It focuses on understanding how environmental exposures influence our health, how we can reduce these risks, and how to participate in health-protective actions (like testing for pollutants, reducing exposure, or supporting health-related policies). Environmental Health Literacy (EHL) combines health literacy and environmental education. It also teaches practical skills like reading, monitoring data, use of protective tools, and speaking up for healthier environments (Finn et., al 2017)

**EL and EHL in Managing Emerging Contaminants**

People can take concrete steps to lower their exposure to harmful substances, for example, by using low PFAS products, filtering drinking water, and avoiding items that release microplastics. Good Environmental Health Literacy (EHL) helps people turn this knowledge into such feasible protective actions. When communities are educated and aware, they can take part in monitoring activities like water sampling and biomonitoring initiatives. Evidence from community-based monitoring projects shows that local sampling and data sharing can lead to real action and safer environments. EHL also helps people understand risk information correctly, reducing both complacency and maladaptive fear especially when official guidance is uncertain or evolving, as is common with emerging contaminants (ECs). Literate communities and health professionals can then demand testing, product safety, and stricter regulations, helping to prevent problems before they start.

## Reducing Health Risks from Emerging Contaminants Through EL/EHL

Mechanisms through which EL/EHL interventions can affect the exposure–health outcome pathway for ECs.

### Knowledge to behavior pathway

Knowing about where emerging contaminants (ECs) come from, how they reach people, and how they affect health helps people understand their personal risk and feel more capable of taking action. This awareness is an important step for changing behavior. Protective actions may include using certified water filters that remove PFAS or other particles, choosing personal-care products without harmful chemicals (Grey, 2018). Avoid microwaving food in certain plastic containers to reduce exposure to microplastics and additives and changing laundry or textile choices to reduce microfibre shedding. However, knowledge alone is insufficient to bring about behavior change. People's ability to change behavior also depends on things like cost, social habits, and local conditions. Effective Environmental Health Literacy (EHL) programs provide information with practical tools—like low-cost filter options and shopping guides and consider inequities in access.

### Community monitoring and advocacy pathway

Community and citizen science programs help people detect and understand contaminants that are not easily visible. When community members are trained in sampling protocols, data interpretation, and communication, they can identify local contamination like PFAS in drinking water, provide credible and independently collected information to authorities and the media, negotiate remediation, exposure mitigation and health monitoring programs (Gray, 2018). A One Health approach emphasizes to connect environmental data with animal and human health indicators, allowing local communities with environmental health literacy (EHL) to play an active role in protecting human health (Tomsho et al.,2024).

### Policy influences and market transformation

When people and healthcare workers are well informed, they can push for better laws, improved product information, and safer industrial practices. For example, consumer demand for PFAS-free products has prompted some manufacturers to reformulate their products. Environmental and health literacy (EL/EHL) helps people continue such advocacy and supports evidence-based policymaking (Binder et al., 2022; Gray, 2018).

## Designing Effective EL/EHL Interventions for Emerging Contaminants

Based on insights from behavior change theories, risk communication research, and empirical EHL studies, effective interventions are guided by several design principles.

## Principles for intervention design

When dealing with emerging contaminants in the environment, interventions aimed at improving people's understanding and acting on exposure risks tend to succeed better when they follow these design principles:

### contextualization

Interventions are more effective when they fit the actual situation of the people they are meant for. This means the information should match local exposure risks, cultural beliefs, language, and economic conditions.

General messages like "chemicals are harmful" usually don't work because people don't feel it applies relates to their daily life or what they can do about it. For example, an EHL review also showed that it is important to understand community-specific exposures and what resources they have, instead of assuming universal responses. By designing interventions based on the local situation, people find them more relevant, increase trust, and are more likely to take action.

### Actionability

It's not enough to increase knowledge people need to be able to do something with that knowledge. Prioritize behaviours and actions that are **evidence-based**, **feasible**, and **affordable** in the local setting. Provide alternatives when the "ideal" choice isn't available or realistic. In EHL studies, interventions that combined both education and practical tool or mitigation strategy. For example, giving people low-cost water or air filter along with information showed measurable reductions in indoor pollution levels and even urinary biomarkers.

### Skill-building:

Effective programs teach practical skills. For example, they show how to read and interpret water-quality reports, how to check product ingredient lists to avoid harmful chemicals, and how to choose and maintain a home water filter or safe disposal method. Learning these skills helps people feel more confident which makes them more likely to change their behavior. In many EHL studies, the "skills" part is often not strong enough, so it is an important area to improve.

### Participatory Approaches

Engaging community members enhances ownership, relevance and sustainability, let local people help design the intervention, collect data, interpretation and plan actions. EHL studies show that real change happens when communities take part. When people have a role, they trust the findings more, feel responsible, and continue behaviour change over time.

**Multi-Channel Delivery**

Combine school curricula, community workshops or field activity, healthcare or clinic settings, social media, and local media, apps, or monitoring dashboards to reinforce messages. Using different communication channels helps reach diverse audiences (children, adults, informal workers) and strengthens the message in different situations.

**Equity Focus**

Exposure to emerging contaminants and the ability to respond often show **inequities**: children, pregnant women, low-income communities, informal workers often face higher exposures and fewer resources to protect themselves. Equity-focused intervention means helping everyone but especially those with the greatest risk and having the least support.

**Evaluation & feedback:** Include rigorousto track what people learn, how their behaviour changes, and how the environment improves. When possible, also measure health indicators to see if exposure is actually reduced. Evaluation also allows refinement: if behaviour isn't changing, you can modify the messages, the way you communicate, or the kinds of support you provide.

**Examples of intervention components**

- **School-based modules:** Age-appropriate lessons on plastic pollution, safe product choices, and local water systems that include hands-on experiments and small community projects.
- **Clinical EHL training:** Short modules for health workers about emerging contaminants, exposure history taking, counsel patients, and referral networks.
- **Community toolkits:** Step-by-step guides to help families for household exposure reduction, including information on low-cost filtration, safe disposal of medications, and laundry practices to reduce microfiber pollution.
- **Citizen science labs:** Training sessions on sampling protocols for water or dust, data-recording tools, and data-sharing platforms that connect communities to academic or government agencies.
- **Risk communication** campaigns**:** Clear and honest messages co-developed with community leaders, sopeople stay informed without unnecessary fear and build trust.

**Monitoring, Evaluation, and Research Priorities**

**Evaluation metrics**

A strong evaluation system is crucial for improving and justifying EL/EHL initiatives. It should examine changes in knowledge and attitudes, track actual behavior changes, and monitor environmental conditions like water, dust, or indoor air pollutants

(Lichtveld et al., 2019; De Michino et al., 2025). When appropriate, ethically approved biomonitoring through urine or blood tests may be used with proper consent and follow-up. Evaluation should also consider broader policy or system effects, including regulatory action or industry changes influenced by community actions, while ensuring data privacy throughout (Kim et al., 2024).

## Research gaps and priorities

Research still needs to fill several important gaps to strengthen EHL efforts. These include testing how well interventions lower exposures and health risks, studying whether education-based approaches are cost-effective, and understandingwhich types of messages resonate with different communities without placing unfair responsibility on individuals. (Finn & O'Fallon, 2017; Zwickle et al., 2014). Long-term research can reveal whether early EHL education leads to lasting and cross-generational benefits (Gray, 2018). Finally, studies should explore how community-collected data can be validated and used within formal regulatory processes.

## Policy and Practice Recommendations

Coordinated action across education, healthcare, research, policy, and industry is needed to strengthen EL/EHL efforts. Educators and community groups should integrate EHL into school curricula, provide multilingual toolkits, and collaborate with health agencies for citizen science (Gray, 2018; Tutu et al., 2025). Healthcare systems must train clinicians in environmental exposure counseling, create referral pathways, and share surveillance findings clearly with patients (Tomsho et al., 2024). Researchers should focus on community-co-designed studies with measurable exposure and health outcomes while advancing understanding of EC mechanisms (Lin, 2025). Policymakers can fund community EHL programs, improve product labeling, encourage safer alternatives, and apply precautionary measures when risks are uncertain. Industry should increase chemical transparency, develop safer products, and support community education and remediation.

## Conclusion

Emerging contaminants pose increasingly complex risks to environment and public health system. Their persistence, complex chemistries, and often low-dose, long-term effects mean that technological controls and regulatory measures alone cannot adequately protect communities. As scientific uncertainty continues and new contaminants are identified, it becomes essential to strengthen approaches that empower people directly. Environmental literacy (EL) and environmental health literacy (EHL) provide this support by strengthening individuals' and communities' ability to understand risks, adopt feasible exposure-reducing behaviors, and participate in monitoring and advocacy efforts. An effective EHL strategy emphasizes more than information. It integrates practical skill-building, locally relevant education, participatory data collection, culturally tailored communication, and collaboration

with health systems and policymakers. When equity is prioritized EHL can help reduce disparities by giving vulnerable populations accessible tools to protect themselves while also contributing to broader policy and industry reforms. EHL can effectively complement regulatory efforts, enhance early identification of emerging risks, and support community-led responses. However, its impact relies on consistent evaluation, long-term investment, and strong partnerships among educators,researchers, health professionals, policymakers, and affected communities. Integrating EHL into larger public-health and environmental systems can strengthen community resilience and create more informed, capable, and health-protective communities.

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# The Developmental Blueprint: Brassinosteroid-Mediated Control of Plant Growth and Shape

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**Abstract**

Brassinosteroids (BRs) play an essential role in lifecycle of plants as they are a group of plant steroid hormone. They influence development, cell division, elongation, vascular tissue formation, flowering, and reproduction. Among them, brassinolide is considered the most active form. This review focuses on how BRs regulate plant growth through specific signaling pathways involving key proteins like BRI1, BES1, and BZR1. These components help transmit BR signals from the cell surface to the nucleus, where gene expression is altered to support growth and development. Plants with impaired BR production or signaling often display stunted growth, late flowering, and reduced fertility, showing how vital BRs are. Beyond development, BRs help plants survive extreme conditions like drought, salinity, heat, and pathogen attacks. They do this by working with other plant hormones and activating defense mechanism, antioxidants and stress-related genes. BR applications has yielded positive agricultural effects on seed development, crop yield, and stress resistance, especially in crops like rice, maize, and cotton. Although significant progress has been made, further research is still required to fully explore how BRs works at molecular level and how they can be used to improve crop resilience and productivity in changing environments.

**Keywords**: Brassinosteroids, Plant development, Phytohormones,Plant architecture, Cell elongation, Cell division, Root development, Shoot apical meristem, Vascular differentiation.

## Introduction

Phytohormones are responsible to regulate growth in plants. Phytohormones activate plant defence in all types of stresses (Malik *et al.,* 2023). Phytohormones are also known as chemical messengers because they regulate plant growth and development including biotic and abiotic factors, and they also maintain the homeostasis allow them to adapt the environment (Peres *et al.,* 2019). Phytohormones like Auxin, Gibberellin, cytokinin,brassinosteroid, Abscisic acid, Ethylene, jasmonates, salicylic acid, strigolactones collectively regulate plant growth and development (Zhou *et al.,* 2023) (Zhao *et al.,* 2021). In thisregard, phytohormones influences physiology and biochemical mechanism of plants and improveit's stress tolerance (Hafeez *et al.,* 2021; Raza, 2022; Raza *et al.,* 2019; Zahra *et al.,* 2018).

Brassinosteroid has emerged as a novel sixth class of phytohormones which plays a role in plant growth and development (Wei and Li, 2016; Nazir *et al.,* 2019). Brassinosteroidare highly-hydroxylated compounds in plants that are very crucial in plant's life. These hormones influence plant development and regulate photomorphogenesis, xylem differentiation, cell elongation, cell division, reproduction including biotic and abiotic stresses. Brassinosteroids are a distinct group of phytohormones, which are distinct from animal-derived steroids, that do not function as nuclear receptors but they function as the cell surface receptor complexes. The most active BR is brassinolide which was purified from >200 kg of rapeseed (*Brassica napus*)pollen and the structure is determined by x ray analysis (Grove *et al.,* 1979). They are most abundant in seeds and pollen of all the plants(Bartwal and Arora 2020). Brassinosteroid also regulate gene expression, cell differentiation, cell division and governs complex cascades of plants (Khan *et al.,* 2022). A significant discovery of brassinosteroid was the identification of brassinosteroid-insensitive1 (BRI1), a known receptor kinase, initiates an intracellular cascade with respect to extracellular perception of BR's (Li and Chory 1997). A significant brassinosteroid hormone is

brassinolide which is used to study physiological outcomes of exogenous steroid phytohormones in plants. Brassinosteroid deficiency causes dwarfism, delayed flowering, short petioles and reduces phenotypical fertility. Genes responsible for brassinosteroid mediated responses are BZR1 (BRASSINAZOLE RESISTANT 1) and BES1 (BRI1-EMS SUPPRESSOR 1), which are also named as BZR2. They regulate brassinosteroidsignaling pathway and control variety of genes in processes such as growth response, amino acid metabolism, cellular signaling and transportation, cell membrane synthesis, nucleo protein complex and cytoskeletal filaments, ecological responses, and hormonal-mediated responses(Sun *et al.,* 2010).

**1. Brassinosteroid Signaling pathway**

Brassinosteroid has a complex signaling pathway, it helps in plant growth and development. This pathway represent that the BR recognize a hormone outside the cell which is plant-specified leucine-rich repeat (LRR) receptor kinase which is present on the plasma membrane. According to previous reports BRI1 interacts with the BRI1 linked receptor kinase BAK1 which controls some of the crucial positive signaling regulators such as BZR1 and BES (Clouse 2011; Manghwar et al. 2022). When there are increased level of brassinosteroid it show dephosphorylation of BZR1, which then process the binding of BZR1 to preserved E boxes. After perceiving the signals from BRs it is passed to BES and BZR1 from a signaling cascade which regulates the genes to be transcribed by the BRs (Aldukhi et al. 2020; Planas-Riverola et al. 2019; Praveena et al. 2020; Tong and Chu 2018). There is another LLR receptor kinase which get involve with the BRI1which is BAK1 and it acts as co-receptor, then the most active form of BR which is brassinolide induce the interaction between BRI1 and BAK1 (Sun et al. 2013). It induces the intracellular signalling including protein phosphatase BSU1, the serine or threonine-protein kinase BSK1, protein phosphatase 2A (PP2A), Glycogen synthase kinase 3 (GSK3)-like kinase Brassinosteroid-insensitive 2 (BIN2), and transcription factors in BZR1 family (Lee et al2020; Wang et al2012).

### 1.1 In absence of BRs:

In absence of BRs in *Arabidopsis thaliana* a gene which is BIN2 which acts as kinase it phosphorylates BES1 proteins, BES1 gets activated and it binds to 14–3-3 proteins and get embedded on the cytoplasmic membrane which is followed by degradation and cytoplasmic retention this prevents transcription factors from entering the nucleus.

### 1.2 In presence of BR:

In vicinity of BR, BR hormone interact with BRI1 receptor along with co-receptor which is BAK1 from this BKI1 get dissociates (which blocks BRI1) from BRI1 receptor. These two receptors phosphorylate each other and formBRI1-BAK1 receptor complex. This complex pass signal to CDG1 (Constitutive Differential Growth 1) and BSK1, and it activates BSU1, which causes removal of phosphates from BIN2 to inactivate it. When it gets inactivated this leads to activation of BZR1 and BES1 gene. BZR1 and BES1 get dephosphorylate by PP2A and get activated which allow the transcription factors to enter the nucleus and regulates the BR genes. PP2A controls BR signalling positively by dephosphorylation of BZR1 and BES1(Abdullahi *et al.,* 2003) .

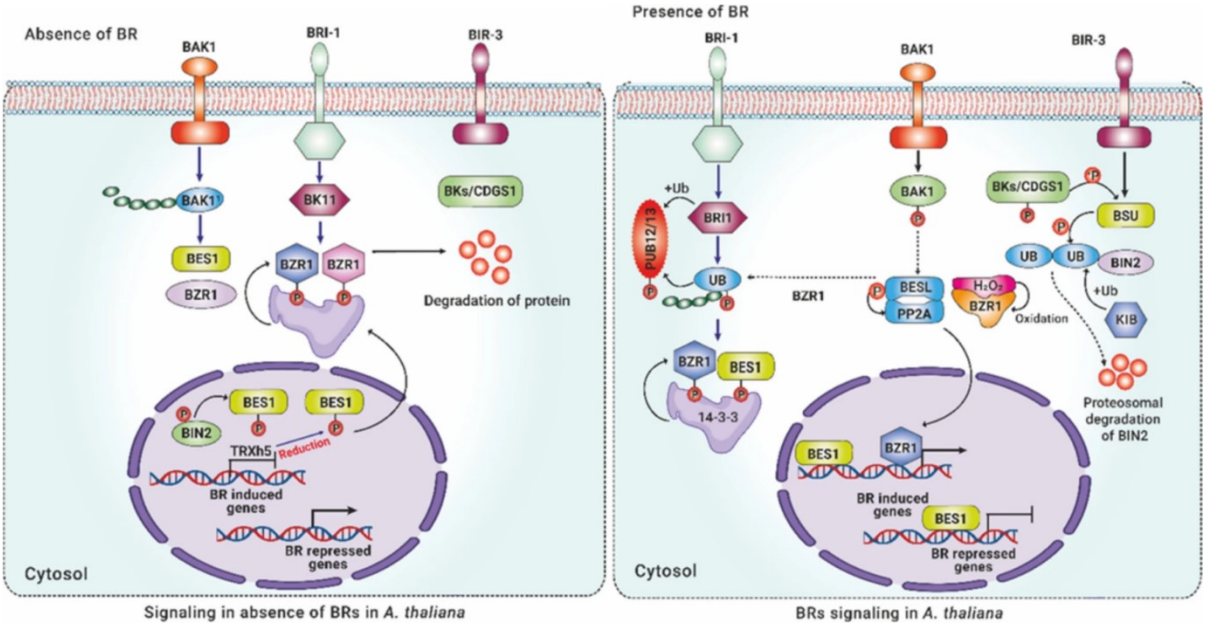



**Fig.1-**Signalling in the absence of BRs and BRs signalling in *Arabidopsis thaliana*(Chakraborty *et al.,* 2025)

## 2. Crosstalk Between Brassinosteroids and Other Phytohormones

The regulation of development and growth happens in plants through a complicated chain of signalling cascades in which interaction happens between plant hormones. The different stress response and developmental process are regulated by Brassinosteroids (BRs), they work in sync plant hormones and control these processes.

**Auxin: -** Auxin and Brassinosteroids is mostly studied among all the phytohormones in plants. Previous research has shown both hormones auxin and brassinosteroids act collectively and regulate elongation in cells, vascular development, regulation of axillary branching and root initiation and development. BZR1 transcription factor collaboratively regulates growth-related transcription factors. This process of coordination promotes organogenesis in plants and also biomass accumulation. BRs regulate the expression of auxin transporter genes in overall plant development.

**Gibberellins: -** Both BRs and gibberellins (GAs) act as plant growth regulators. Both hormones control cell expansion and prevent dwarfism in plants by interrelated signalling cascades. When the GAs are not present, DELLA proteins bind to BZR1 and BES1 transcription regulators and act as master repressor. When the amount of GAs increases in plants, DELLA proteins start degrading. This coordination helps in shoot growth, leaf enlargement, and reproductive maturation. These hormonal-mediated interplay allow plants to behave differently in different environmental conditions (Li & He, 2013).

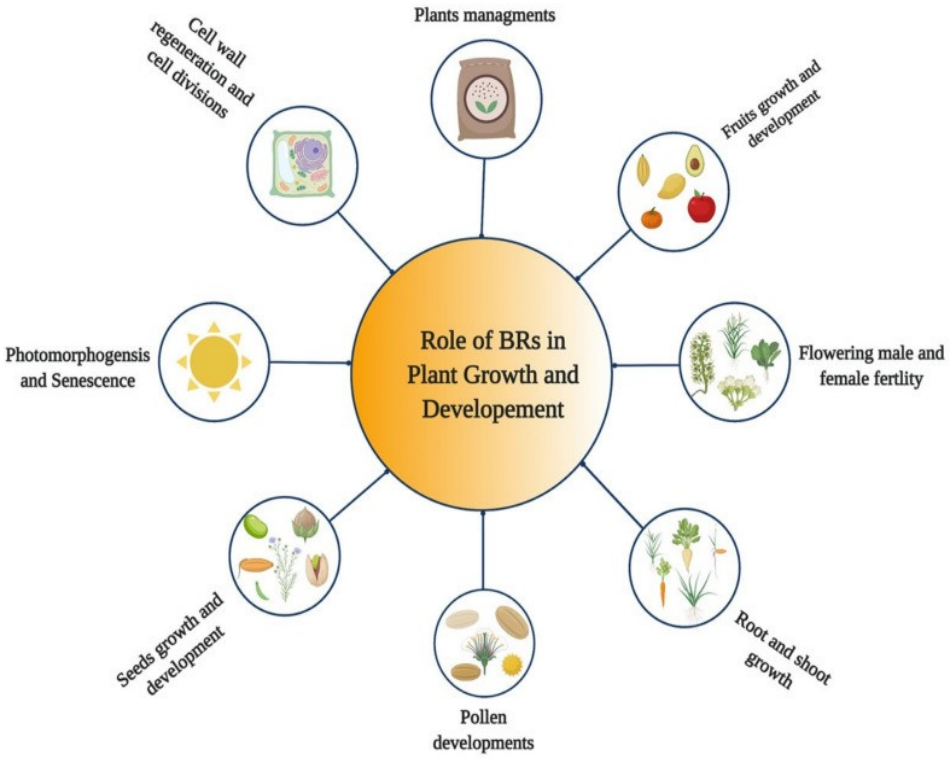
**Ethylene:-** The coordination of ethylene and BRs regulate important physiological conditions like ripening of fruits, apical hook formation, and root development (Jiroutova*et al.,* 2018). The association of both the hormones is dose dependent. At natural physiological conditions, ethylene synthesis is suppressed by brassinosteroids: the ACS (the rate-limiting enzymes in ethylene production) promotor is bound by the two active genes which is BZR1 and and starts inhibiting them. When there is a high concentration of BRs the action is reversed by increasing ACS proteins, which helps and accelerate the ethylene (Jiroutova*et al.,* 2018).

**Abscisic Acid:-** Abscisic Acid (ABA) is known as growth repressors and stress respond mediator, its relationship with BR is antagonistic because they act as growth promotor (Kour *et al.,* 2021). ABA signalling represses BR regulatory pathways to stop the growth of plant for preserving their cellular energy for different environmental conditions (like heavy metal or drought stress) (Kour *et al.,* 2021). BR signaling regulate ABA-mediated growth supression from becoming more severe (Kour *et al.,* 2021).

**Cytokinin:-** Cytokinin and BRs both drive cell division but both work antagonistically while organizing root formation.In the process of development of root, BRs and auxins initiates cell differentiation and stem elongation, whereas cytokinins helps in cell division (Liu *et al.,* 2014). BRs protect auxin in the process of transporting networks while Cytokinins uses genes like ARR1 to suppress auxin transport networks (PIN proteins (Liu *et al.,* 2014).

## 3. Brassinosteroid as a key regulator in plant development

Brassinosteroid are type of steroid based hormone, that drive morphogenesis and proliferation in plants (Lin, 2020; Soares *et al.,* 2016). BRs regulate processes such as cell expansion, vascular development, cell division, in maintaining stem cells, help in lengthening of cells, and help plant to shift from vegetative to flowering stage(Fang *et al.,* 2019), (Manghwar*et al.,* 2022). Furthermore, they are also involved in different processes such as hypocotyl elongation (Oh *et al.,* 2014), shoot and root growth (Lv*et al.,* 2018), patterning of stomata (Khan *et al.,* 2013), growth of pollen tubes, reproductive development, xylem formation (Saito *et al.,* 2018), treachery element differentiation and even in senescence (Bajguz*et al.,* 2020). They trigger the cell division cycle during seed germination, assist in proton transport, improve heat tolerance, increase tiller number and modify leaf shape and size. By modifying there signalling and production or spraying it externally can lead to higher crop production (Jaillais& Vert, 2012; Jaiswal *et al.,* 2020; Zhu *et al.,* 2015).




Manghwar et al. 2022

Fig 2:- Role of Brassinosteroids (BRs) in plants.

## 4. Transcriptomic and Molecular Controls

At the molecular level brassinosteroids control large networks of genes (Chen et al. 2021) established that BRs can activate different WRKY genes which are WRKY46, WRKY54, and WRKY70, which help in modulating botanical hormones. A previous story showed that a gene which is known as SDG8 (histone lysine methyl transferase) which participates in BR signalling (Wang *et al.,* 2014). When this gene is knocked out stunned growth this seen and they cannot give response to BR, and this confirms its role in BR regulating gene activity. BR influence seed development in Arabidopsis by regulating its size, weight, and number by transcriptionally modifying their genes and pathway and affect the morphogenesis of the ovule which later becomes a seed(Huang *et al.,* 2013; Jiang *et al.,* 2013). Under low nutrient conditions, BRs also help plants uptake nitrogen by elongating primary root systems, a phenotypic response controlled by the *BSK3* gene (Jia *et al.,* 2019).

## 5. Role of Brassinosteroid against different stresses in plants

Brassinosteroids play important role in saving plants from different biological and physiochemical challenges(Anjum *et al.,* 2011; Divi *et al.,* 2016). Brassinosteroid enables plants to adjust in different environmental stresses, resistance from pathogen, cell elongation for its better growth and development ((E. J. Kim & Russinova, 2020). Since they are used as biostimulants and protect plants from abiotic stress and increase the efficiency of plants. Brassinossteroids help in reducing different stresses like cold, drought, heat, salinity, biomass portioning, antioxidant enzyme, detoxification. They protect from oxidative damage, heavy metals toxicity and pathogen attack (Hao *et al.,* 2013; Rajewska *et al.,* 2016). BRs work with other hormones and they control multiple metabolic processes in plants. These all-regulatory processes means that they protect plant from different environmental factors.

Several studies have shown BRs regulate different genes in various crops for protecting them from drought, virus, cold, etc.

***Key Experimental Observations from Different Studies:***

- **Drought Stress Regulation:** Previous studies shows that it plays critical role in drought stresses in species like Brassicaceae such as *Arabidopsis Thaliana* and *Brassica Napus* and wheat (Kagale et al. 2007). When gene of Arabidopsis AtDWARF4 gene is been overexpressed in b. napus it shows drought resistance (Sahni et al. 2016). By using BRs so they activate resistance genes and antioxidant enzymes.
- **Viral Resistance and Biotic Defense:** The disease in barley caused by *Helminthosporium teres* Sacc which is reduced by spraying 24-epibrassinolide (Hussain *et al.,* 2020) . BR signaling is used to induce BR induced resistance to plant viruses.
- **Heavy Metal and Low Temperature Stress:** When BRs like 24-epibrassinolide and 28-homobrassinolide (HBL) has been given to plants so they reduce toxicity of heavy metals (Soares *et al.,* 2016). Additionally, it was

found that exogenous BR administration increased pepper resistance against low-temperature stress.

- **Freezing Tolerance Mechanics:**In a study it shown that BRs two important component reduced freezing tolerance in plants. GSK3-like kinases (involved in BR signaling, bin2-3 bil1 bil2) there loss of function shows more freezing resistance but when BIN2 is overexpressed in plants, so they become sensitive for freezing. If the BIN2 is more in plants, it has lower resistance in plants when it is less it shows plants as stronger. If level of BES1 and BZR1 is increased, it shows more freezing resistance in plants (H. Li *et al.,* 2017).
- **Salt Stress Response and Genetic Integration:** UBC32 is a enzyme that gets activated in stress condition in plants which is found in ER membrane gets connected with the ERAD process and BR-based growth and salt stress tolerance. When UBC32 gets mutated so BRI1 starts accumulating and BRI mutants activate BR signaling pathway means even in mutant condition they start BR signalling (Cui *et al.,* 2012).
- **Photosynthetic and Hydrogen Peroxide Pathways:** In another study the effect of BR was seen when cadmium metal was affecting tomato plant especially on oxidative stress aur photosynthesis. When cadmium was in higher level there was decrease in photosynthesis level, the expression of enzymes like (carbonic anhydrase and nitrate reductase), lowers the quantity of leaf water potential. When brassinosteroid were sprayed the photosynthetic activity, antioxidant defense gets better, and the cadmium amount became less in quantity. BR and ABA both helps in making H2O2 their function is to protect plants from PQ oxidative and heat stress. BR and ABA activate RBOH1 gene, NADPH oxidase enzyme, apoplastic H2O2 which results in stress tolerance against PQ and heat (Zhou *et al.,* 2014).

## 6. Future perspectives

The discovery of Brassinosteroids is a breakthrough in the understanding of plant growth regulation & stress adaptation. Despite extensive research over the past few decades, many aspects of BR biology remain unclear. Valuable insights have been

obtained into BR-mediated signalling networks via the contemporary advancements in genomics, transciptomics, proteomics & metabolomics. However, the actual mechanisms administering interactions between BRs & other hormonal pathways require further investigation. Under changing environmental conditions, the comprehension of complex molecular interactions shall be essential for the development of innovative strategies that will aim at improving crop productivity (Planas-Riverola *et al.,* 2019)

The modern genome-editing technologies, specifically CRISPR/Cas9, offer extraordinary opportunities for the manipulation of BR synthesizing &signalling genes. Targeted modification in genes such as BRI1, BZR1, BIN2 & DWF4 may facilitate the development of crops with refined growth characteristics, improved yield potential & greater tolerance to abiotic & biotic stresses (Manghwar*et al.,* 2022; Oppermann *et al.,* 2022). Additionally, further advancements in synthetic biology shall enable the engineering of optimized BR signallingpathways for crop improvement. The development of next-generation crop varieties that are capable of maintaining productivity under adverse climatic conditions shall be facilitated by such approaches.

The advancements in BR-based formulations & nanotechnology-assisted delivering systems are a promising field of research. The limited stability & reduced efficiency under field conditions negatively affect the traditional applications of hormones. Delivery systems mediated by nanoparticles enhance BR stability, targeted delivery & control the release of hormones, thereby enhancing their agricultural effectiveness (Lira *et al.,* 2020; El-Soud *et al.,* 2023). Evaluation of long-term ecological impacts & field-scale applications of BRs across diverse species should be the prime focus of future studies. Ongoing research on BR biology & its applications in agriculture may play a crucial role in achieving sustainable crop production & food security across the globe.

## Conclusion

Plants are under constant stress which could be due to biotic and abiotic factors affecting its growth and development and resulting in reduced crop yield. To ensure survival under such variable conditions, a complex adaptive mechanism have been promoted by plants, which includes synthesis of a variety of phytohormones. Among these, brassinosteroids (BRs) have emerged as key regulators of diverse physiological and developmental processes. Apart from boosting growth of plants BRs play a key role in enhancing plant tolerance in variety of environmental conditions by modulating antioxidant defence systems and stress-responsive gene expression. In recent times the importance of BR in plant biology has gained widespread attention recognising evidence supporting their dual role in development and stress resistance. Although ample amount has been done on the subject further progress and studies are needed to fully understand the molecular mechanisms underlying BR mediated regulation in plants. Continued research in the field will be essential for recognising the potential of BRs in developing stress-resilient and high-yielding crop varieties

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# Relevance of Indian Traditional Knowledge in Advance System of Medicine.

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## Abstract

Indian traditional medicine has evolved through unique historical paths, influencing health and healing across India's diverse regions. Various traditions have coexisted for centuries, each taking different forms. Knowledge and practices from these traditions remain alive, albeit in varying forms. Ayurveda, Siddha, Unani, and Naturopathy are the most recognized systems today. Meanwhile, practices like Hatha Yoga, Sowa Rigpa, Tibetan Medicine, and Homeopathy, while important, lack official recognition. Local healing practices also thrive, reflecting ecological and cultural adaptations. Research shows Ayurveda and Unani are the primary systems transmitted among practitioners. Despite significant differences from biomedicine, the latter often informs studies on these traditions' safety and efficacy. (Nambiar et al., 2014)

**Keywords:** Indian traditional medicine, Ayurveda, Siddha, Unani, Naturopathy.

## 1. Introduction

Throughout history, human sentiment—a yearning for balance, equilibrium, and symmetry—has sought expression in myriad ways. The natural world abounds with such examples, from the Fibonacci sequence to fractals to crystal growth. As human societies and cultures have evolved, the quest for balance has arisen in religion, symmetry in architecture, rhythm in poetry, and harmony in music. In no domain is the expression of balance more important than in health. Both public health and personal health—in disease prevention, health promotion, clinical care, the design of health systems, and health—all benefit from a balanced approach that incorporates a sufficiently diverse portfolio of knowledge, attitudes, and skills. The balance may be between different health systems (e.g. traditional, complementary, and modern); between disciplines in modern health care (e.g. medicine, nursing, nutrition, and

physiotherapy); among biophysical, biosocial, cultural, behavioral, economic, environmental, ethical, preventive, psychological, social, spiritual, and technological determinants; and between health, technology, and other domains (Bhargav et al., 2022) ; (Nambiar et al., 2014).

The relevance of healing systems and health-care systems to well-being—particularly for communities that retain a close relationship with their traditions—renders particularly urgent the exploration of balance within Indian traditional medicine. Various Indian systems remain actively practised, with the still-expanding Ayurvedic system particularly prominent. A rich corpus of documented procedures exists, yet the interaction of Indian traditional healing with technology provides few empirically grounded comparisons.

## 2. Historical overview of Indian traditional medicine

The historical development of Indian traditional medicine (ITM) can be traced to the Harappan civilization. The 18th and 19th centuries are a significant period during which the country witnessed historical conquests, including Persian, Greek, and mainly the Mughals, leading to the incorporation of Unani into the traditional folkloric systems already in existence. With the advent of British rule, Ayurveda was highly neglected, while topics such as Unani gained momentum. However, recently, Ayurveda has engaged the interest of many people in different parts of the globe, while other Indian systems such as Unani and Siddha continue to flourish in their own zones (Patwardhan et al., 2005).

## 3. Philosophical foundations and epistemologies

Classical Indian medical systems are described as having a holistic approach towards health and well-being (Hankey & Kale, 2023). Underlying the assertions of various systems of Indian medicine are elaborate ontological and epistemological foundations that differ markedly from those of biomedicine. Philosophical frameworks do not constitute contemporary medical theory but function as the interpretative lens through which texts are examined, practices are understood, and knowledge is transformed

into applied, contemporary health care (Khanna, 1987). Medical ontology is concerned with understanding the nature of health and disease—including the constitution of matter and the relationship between the human body and the environment—while epistemology defines legitimate knowledge and valid methodologies through which it can be validated.

## 4. Current state of Indian traditional medicine systems

Traditional Indian medicine embraces articulated systems of knowledge and practice, with distinct philosophical foundations and epistemic approaches. At present, systems officially recognized in India are Ayurveda, Unani, Siddha, Sowa Rigpa, and Naturopathy, complemented by tribal medicines for certain communities. Primary health-care services are delivered by local practitioners; they operate outside the public-health infrastructure, although integration has gained ground. Several factors influence the choice of traditional treatments, including safety, accessibility, and affordability. Clinical application focuses on chronic and lifestyle-related conditions (Chattopadhyay & Bochenek, 2014). Satisfactory documentary evidence for health outcomes is available for Ayurveda (Remedy, practice, and system) and Unani (Kashf-ul-Aila), collectively covering 83 diseases linked to a diverse range of agents; the documentation retains relevance, though mainly for practitioners (Patwardhan et al., 2005). Several national-level independent organizations provide training, consultancy, and accreditation. Bureaucracy surrounding official endorsements can hinder participation of private institutions and industry associations in quality assurance and standardization activities.

## 5. Health outcomes and evidence base

Global interest in health, well-being, and quality of life has grown markedly in recent decades. Medical systems across the world, including Ayurveda, Siddha, Unani, Chinese Medicine, and Naturopathy, address these issues holistically. Post-independence, the re-emergence of these systems has been remarkable, with the Ministry of AYUSH (Ayurveda, Yoga and Naturopathy, Unani, Siddha, and Homeopathy) established in 2014 to promote and protect them. Scientific scrutiny of

these systems is also increasing, with controlled clinical trials, observational studies, and systematic reviews evaluating clinical effectiveness undertaken, as well as considerable academic research on mechanistic understanding. Such evidence-generation and validation—the theme of the present section—is crucial to facilitating further research and the establishment of integration models (Patwardhan, 2014). Efforts supporting and validating classical systems remain critical, together with moving towards personalised, predictive, preventative, and participatory medicine, the potential offered by genomics, and addressing the contemporary demand for a wider variety of treatment and interventions. Research priorities are determining the systems of interest, the most appropriate outcomes, the patients of greatest relevance, and suitable measurement methodologies, with standardisation of reporting and indication indicators also key.

Ayurveda has rich clinical traditions and extensive scholarly material spanning thousand of years, with two streams of textual scholarship continuing today (Nambiar et al., 2014). Several clinical facilities—hospital/clinics, community-based centres, and research institutes providing curative, palliative, and preventive services—demonstrate the interest and support for traditional medical systems. National health systems integrating traditional systems within curative, preventive, and health-promotion practices have been established in several countries.

## 6. Technology and innovation in traditional medicine

Contemporary advances in various fields of technology and innovation are being adopted in the practice of traditional medicine, thereby further facilitating the spreading of ayurvedic and other complementary health care systems (Patwardhan et al., 2005). Technology plays a critical role in the capture and analysis of relevant data, enabling effective diagnosis and diagnosis screening support, and optimization of therapy selection in conjunction with the ayurvedic medical system. Implementation of bioengineering and related innovations also provides the possibility of assisting health care delivery and health promotion in the cosmopolitan urban environment. Different forms of health economics, cost-benefit analyses, and associated studies

have been carried out with various indigenous traditional health systems with a view to working out the cost-effectiveness of treatment accordingly and to exploring the actual need for such measures. The emergence of digital health for health-care delivery and promotion is now emerging in a context similar to those in which traditional medicine is been carried out.

The active systems of the Ayurveda, Siddha, Naturopathy, Unani, Yoga, and Zootherath and the associated traditional medicine systems that have developed in the subcontinent have been drawing increasing interest from various quarters for their perceived role in diet-integrated health delivery systems and for making available the indigenous system such as yoga and the considerably ancient siddha system for preventive health promotion.

**7. Risk, regulation, and quality assurance**

The integration of information and communication technologies in traditional Indian medicine delivery raises the risk of unethical practices and adverse events due to insufficient regulation. Regulation must govern manufacturing, practice, safety, quality of medicines, and public awareness. Quality control should cover all stages from harvesting to administration. Regulatory frameworks for traditional medicine include comprehensive, prohibitive, permissive, restrictive, and anarchic models. Comprehensive frameworks address all areas, while prohibitive ones disallow any activity. Permissive frameworks regulate some aspects, restrictive ones limit practitioners, and anarchy has no rules. Pharmacovigilance systems are crucial with the rise of telemedicine and digital health. Datasets on adverse drug reactions should be made available to inform all stakeholders, ensuring the quality and safety of traditional formulations adheres to international standards. Many traditional systems utilize polyherbal formulations, complicating compliance with Good Manufacturing Practices, making standardization critical. Establishing national standards and promoting international frameworks through organizations like the World Health Organization and Central Drug Standards Control Organization is essential. Furthermore, ensuring cross-border compliance for standardization and quality

assurance is necessary, with laboratories supporting packaging, labeling, and stability analyses. (Nambiar et al., 2014)

## 8. Ethical, cultural, and social considerations

Cultural and historical legacies shape human sensitivities to ethical, moral, and spiritual beliefs and exploration. Being one of the oldest civilizations, India, from the time of the Vedic era (1500 BCE onwards) to the present empowers numerous social, cultural, scientific, and technological discourses. Pertaining to health, Ayurveda, Siddha, Unani, and other traditional systems arose, flourished, and despite longstanding opposition still exist in parallel with mainstream takers. A sizeable section of Indian society has a strong inclination toward these systems often to the extent of overlooking the modern approach, highlighting the importance of proper choice and informed consent to be given to the clients (Mishra & Nambiar, 2018) concerning any proposed intervention. Certain communities still practice folk medicine under their local health traditions, often opting for the ceremonial and superstitious ritual over modern or any scientific techniques and advice. This, once articulated and established properly through scientific review with sufficient societal outreach can also be effective and plays a pivotal role in health governance for the country, long considered a decayed, obsolete, and dead system by the mainstream.

Educational curriculum and preventive measures exist and thrive for all types of health governance, and thus proper attention can be given accordingly when required. The ethical and cultural, as well as the moral nature of every type of intervention, needs to be adopted and considered to ensure better maintenance of the Indian health care system.

## 9. Models of integration with modern healthcare

Health systems worldwide are increasingly exploring models for integrating traditional health practices with modern healthcare. Several different approaches have emerged, affording varying degrees of integration. Progressive models permit autonomous co-management with collaborative governance; integrated closely,

traditional practices are offered alongside mainstream modalities within formal health settings, either in independent units or through referral networks; at the farthest extreme, traditional and modern services are treated as parallel systems with disconnected registration, training, and regulation—yet despite their apparent separation, practical and associative links may still be privileged. These diverse integration frameworks highlight the role of politics, culture, and institutional dynamics alongside specific health-system characteristics in shaping the interplay between alternative and conventional health systems.

India's healthcare system displays tendencies across this spectrum. An influential model of integration, developed by the National Institute of Mental Health and Neurosciences (NIMHANS), provides a compelling example of the middle ground where traditional practices and modern medicine are actively combined to broaden treatment options and improve overall effectiveness (Bhargav et al., 2022). The Indian system also demonstrates characteristics of a parallel approach, especially within the ayurvedic sector, where practitioners of modern biomedicine, even when lacking formal ties to the predominantly allopathic system, nevertheless exhibit higher rates of recognition and interactivity (Nambiar et al., 2014).

## 10. Case studies of balance between health and technology

Indian Traditional Medicine (ITM) has been historically and philosophically pivotal to the subcontinent and beyond. Case studies of initiatives promoting ITM as a complement to biomedicine—while adopting technologies like Artificial Intelligence, Telemedicine, mHealth, and Electronic Patient Records—illustrate how this balance is pursued. At the National Institute of Mental Health and Neuro Sciences, Yoga complements traditional medicine; lush gardens foster creativity. Ayurveda addresses chronic lifestyle disorders through technologies like Electronic Health Records (EHR), Medication Identification Systems (MIS), and Thermography (Bhargav et al., 2022). The Tamil Nadu State Rural Health Mission integrates Siddha into biomedical services; an animated mobile application disseminates knowledge on natural hygiene and the "Triple six" principles to prevent vector-borne diseases (Reddy et al., 2022).

An Ayurvedic eHealth Centre enables distant consultations statewide; an Android app connects patients and practitioners; an Interactive Voice Response System (IVRS) disseminates preventive and promotive health information; an Ayurvedic Digital Record System consumes less bandwidth and is accessible to illiterate users (Stanieri et al., 2017).

## 11. Challenges and opportunities for policy

Integrating Traditional, Complementary, and Alternative Medicine (TCAM) into national health systems presents both challenges and opportunities for health authorities worldwide. Policy frameworks for TCAM must navigate regulatory approval processes, quality assurance mechanisms, training requirements, and the broader contexts in which these systems operate. Addressing these challenges while recognizing TCAM's potential to improve health service coverage is particularly important in countries where the capacity of formal healthcare systems is limited (Nambiar et al., 2014). Such is the case in India, where TCAM policies are therefore directly relevant to the revitalization of primary health care in the country (Mishra & Nambiar, 2018).

Traditional medicine offers a complementary approach to addressing the health needs of marginalized populations and providing preventive care. Organizational models describe a variety of integration and collaboration options between modern healthcare systems and TCAM. The demand for TCAM is often accompanied by scepticism regarding its efficacy, and research into the clinical effectiveness of TCAM approaches remains a priority. Efforts to demonstrate safety and efficacy need to be accompanied by an understanding of how evidence is defined within different systems of knowledge.

## 12. Future directions and research priorities

New knowledge is developed, validated, and transferred through varied, context-dependent pathways (Bhargav et al., 2022). Priority topics for research on the integration of Indian traditional medicine with modern health care include: systems-

level analysis of traditional medicine and of integration in public health, education, and clinical practice; the impact of exposure to traditional medicine on practitioner perspectives; the relationship between textual analysis of historical medical treatises and current practice; access barriers, differences in functioning, and out-of-pocket expenditure on selected types of traditional medicine; and the influence of regulatory status on safety and legitimacy (Nambiar et al., 2014). These questions can be examined by collaborations among institutions possessing complementary expertise, resources, and data sets.

## 13. Conclusion

The study addressed the relevance and integration of Indian traditional medicine in the health-technological era, clarifying the balance between health and technology, and tracing the historical evolution of traditional medicine in the Indian subcontinent. Indian traditional medicine remains relevant, with ample opportunities for integration with modern healthcare. Options for institutional engagement, lay understanding, document analyses, conceptual groundwork, and pluralism, epistemology, and evidence are available. Wellness, a pressing need and significantly impacted by technological innovation, can serve as an entry point for increased inter-system engagement.

Indian traditional medicine has a long history and diverse landscape, comprising distinct traditions and systems. Ayurveda, Siddha, Unani, and Yogic traditions evolved in different regions of the subcontinent, informed by local ecological, climatic, and socio-cultural factors. The Ayurveda tradition, Gupta period (4th–6th century CE) to early modernity (17th–18th century), exemplifies system-specific, non-linear evolution. Diverse contributions during early modernity intensified interaction with colonial biomedical models while triggering the emergence of competing epistemologies, including anti-colonial critiques, rationalism, and enlightenment approaches (Bhargav et al., 2022) ; (Nambiar et al., 2014).

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