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G.B. Pant National Institute of Himalayan Environment
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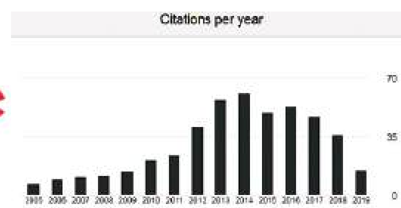

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COMMUNITY-BASED SOLID WASTE MANAGEMENT FOR SUSTAINABLE DEVELOPMENT IN THE INDIAN HIMALAYAN REGION

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ABSTRACT

At present, a lot of efforts have been made to find an effective solution to the problem of waste management globally. One of the crucial factors, which is being emphasized today, is the role of community in waste management. The collaborative involvement of the community in waste segregation, recycling, composting, and responsible disposal practices not only helps in reducing the burden on municipal bodies but also develops a sense of ownership and accountability towards the environment. Successful examples worldwide have demonstrated that when communities are aware, empowered, and integrated into the waste governance frameworks, the waste management systems becomes much more efficient, inclusive, and resilient. This paper emphasizes the role of community-based solid waste management (SWM) in the Indian Himalayan Region (IHR), where the challenge of waste management is already intense due to ecological fragility and further intensified due to rapid urbanization. Community-led initiatives, with the help of a combination of traditional practices and modern approaches, can bridge the gaps in infrastructure required, promote circular economy principles, and generate livelihood opportunities. Ultimately, community involvement can transform the process of waste management from being completely government-centric into a shared responsibility, which helps in ensuring environmental sustainability, public health protection, and long-term resilience in mountain ecosystems.

INTRODUCTION

The Indian Himalayan Region (IHR) about 2,400 km across the northern border of India, covering an area of about 533,604km2 comprising 16.2% of the total geographical area of the country (ISRO report 2016; Aayog 2018). Administratively, eleven states and Union territories i.e. Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya are fully covered in IHR, while West Bengal and Assam are partially covered including only the hill districts. The region is one of the largest producers of waste, with nearly 4996 Tonnes per day (TPD) of waste production. Poor waste disposal and processing facilities in the Himalayan region are harming the ecology in this region. Of the total waste generated, 4580 TPD is collected, and only 2289 TPD is treated, and 748 TPD is landfilled (Table 1, CPCP 2021). Thus, a major part of the waste generated and not treated is either dumped in landfills or thrown across the mountains. Mountain tourism has proved to be a major cause of environmental degradation and water pollution in IHR. This is further exacerbated by the absence of proper infrastructure for waste management and implementation of solid waste management rules due to which waste contaminates not only the soil and land but also the springs and other water bodies in the mountains.

Table 1: Status of waste generation, collection and treatment in IHR

S. No.	State	Solid waste generated (TPD)	Collected (TPD)	Treated (TPD)	Landfilled (TPD)
1	Arunachal Pradesh	236.51	202.11	Nil	27.5
2	Himachal Pradesh	346	332	221	111
3	Jammu & Kashmir	1463.23	1437.28	547.5	376
4	Manipur	282.3	190.3	108.6	81.7
5	Meghalaya	107.01	93.02	9.64	83.4
6	Mizoram	345.47	275.92	269.71	0
7	Nagaland	330.49	285.49	122	7.5
8	Sikkim	71.9	71.9	20.35	51.55
9	Tripura	333.9	317.69	214.06	12.9
10	Uttarakhand	1458.46	1378.99	779.85	-

Source: Annual Report on Solid Waste Management (2020-21), CPCB, Delhi

Solid waste refers to discarded materials in a solid state that are unwanted and no longer useful. These materials originate either during the manufacturing processes or post-use waste generated in domestic or commercial settings. Categorized into several types, solid waste includes residential, industrial, commercial, institutional, municipal, mining, construction and demolition, agriculture and Biomedical waste (Table 2, Hapuarachchi, 2024, Meena *et al.,* 2023). Solid Waste Management (SWM) infrastructure plays a significant role in sustainable development in the IHR. The lack of SWM facilities for collection, segregation, processing, and disposal of waste has emerged as a major issue in the IHR. SWM is more difficult and challenging in highlands than in plain areas due to the topographical configuration, difficult connectivity and vulnerability to natural hazards and disasters (Thakur *et al.,* 2021). Since proper SWM facilities are not in place, open burning is practiced majorly for the disposal of waste. Open burning has adversely affected the ecosystem. The release of major pollutants, including black carbon into the air, which are often linked to glacier retreat (Thind *et al.,* 2019). The other informal means of waste disposal practiced in the region include the dumping of waste in the streams and rivers, resulting in pollution of the freshwater bodies, even thousands of kilometres downstream. To overcome this problem, a systematic way of collection and segregation of MSW plays a very significant role. Several methods including waste recycling, resource recovery from Waste to Energy facilities and waste disposal through sanitary landfills are some of the technologies for waste management and converting waste into valuable products (Berardi *et al.,* 2020). However, to make the method most effective, and for its proper implementation and sustenance in the IHR, it should be possible through public participation, necessary finances, capacity building, and selection of specific waste technology for the region. The concept of Integrated Solid Waste Management, with community participation can prove to be very effective in the hilly region.

Table 2: Classification of solid waste based on source of origin

S. No.	Source	Waste Generators	Examples of waste
1.	Residential	Household activities	Food waste, plastic waste, paper, glass, metals, etc
2.	Industrial	Manufacturing units, Processing plants, Power Plants, etc.	Hazardous waste, metals, special waste, etc
3.	Commercial	Hotels, Restaurants, Markets	Food waste, plastic, paper, etc
4.	Institutional	Schools, Colleges, Offices,	Paper waste, food waste, plastics, et
5.	Municipal Services	Street cleaning, recreational parks, water treatment plants and sites	Sludge, etc
6.	Mining	Open-cast/ underground mining	Ash or other inert material
7.	Construction and Demolition	Construction sites, demolition and reconstruction of buildings, roads, etc	Wood, metals, steel, concrete, etc.
8.	Agriculture	Crops, vineyards, crops, dairy farm, etc	Agricultural waste, pesticides, plastics, etc
9.	Biomedical	Hospitals, Nursing homes, Pathology labs, etc	Needles, syringes, glass, dressings, etc

Source: Meena *et al.,* 2023

INTEGRATED SOLID WASTE MANAGEMENT

Integrated waste management is commonly defined as technological integration for sustainable waste management to protect the environment and human health, specially emphasizing on resource use efficiency (Memon, 2010). It employs a combination of multiple methods and strategies to manage waste in an environmentally safe, economically viable, and socially acceptable way. Unlike traditional waste management system, which often relies on waste collection and disposal, ISWM emphasizes on the entire lifecycle of waste, from cradle to grave i.e. from generation to final disposal, while prioritizing waste minimization, resource recovery, and environmental protection.

KEY PRINCIPLES OF ISWM: The four key principles of ISWM are:

Waste Hierarchy:

Reduce: Minimize waste generation at the source as much as possible.

Reuse: Extend the life of products/materials, bring them to another use, before they become waste.

Recycle: Process materials to convert into new products.

Recovery: Valorisation of waste (e.g., energy recovery through methods like incineration, biogas).

Disposal: Land filling as the last option.

Sustainability: Integration of environmental protection, economic feasibility, and social acceptance.

Stakeholder Involvement: Participation of households, community, local governments, industries, private sector, and NGOs.

System Integration: Coordination of all the processes, namely, waste collection, segregation, treatment, recycling, and safe disposal.

ROLE OF COMMUNITY IN ISWM

Waste management has numerous aspects to it, including economic, social, political, legal, environmental, and social.

For community involvement in waste management, the social aspect has to be especially taken into consideration (Bui *et al.,* 2022). The social aspects of ISWM mainly include the patterns of the different types of materials used by the society i.e. the type of waste generated, the amount of waste generated, various methods that are used to dispose the waste, their willingness in waste reduction and minimization and the extent to which the waste is segregated into different kinds. The attitude of the community strongly influences the extent and type of waste collection and disposal technique undertaken by the concerned authorities. Community-based solid waste management projects are activities carried out by members of communities to clean up their neighbourhood and/or to earn an income from solid waste. For instance, community members play a key role in collection of solid waste, sale of recyclables, recycling and composting activities. Community participation in solid waste management is always required, because solid waste management is a continuous maintenance system. Local community can participate in several ways to contribute for waste management. This can range from adapting to behavioural change, the contribution of cash and labour to consultation, involvement in administration, management and decision-making. Involvement in decision-making is often the highest level of community participation. The importance of community participation can be viewed with a broader scope, not only focusing on waste management. First, community participation can effectively target resources efficiently. This is because through community participation, community becomes willing to share their ideas and opinions. It is a way to get know the needs of the community. Second, it can allow two ways communication and allow the community to participate, through which conflicts and information can be delivered effectively. Third, community participation offers a new thinking and innovative ideas from community. Forth, by community involvement in planning and decision making, community will have the responsibility and sense of ownership. As the community will feel that they are also involved in a project. Fifth, it is a process of empowering people and it is a way to sustainable planning and development. Focus should be laid on the involvement of people along with the initiatives of concerned governmental authorities by linking community-based collection system to the municipal system.

Community participation not only ensures waste reduction at source through the adoption of sustainable consumption practices like reduce, reuse, and recycling, but also helps in enhancing the efficiency of segregation, collection, and resource recovery processes (Fig 1). Segregation of biodegradable, recyclable, hazardous, and inert types of waste at the household level allows more effective composting, recycling, and energy recovery, thereby reducing the volume of waste requiring land filling. Furthermore, community-led initiatives such as using decentralized composting units, biogas plants, and material recovery facilities considerably reduce the burden of waste management on the municipal bodies and also generates employment opportunities for the locals. Active cooperation of door-to-door collection services and the inclusion of the informal sector, particularly waste pickers, into organized systems further strengthens the ISWM practices. Along with playing operational roles, communities also contribute towards effective waste management by promoting awareness, encouraging behavioural change, and promoting eco-friendly practices such as plastic-free events and localized e-waste collection drives. Additionally, community-based monitoring and engagement with resident welfare associations (RWAs) and non-governmental organizations (NGOs) creates accountability mechanisms that improve the reliability of municipal waste services. In this way, community involvement helps in transformation of citizens from being passive generators of waste into active stakeholders of waste management, ensuring environmental sustainability, public health protection, and long-term efficiency of ISWM systems, along-with community empowerment.

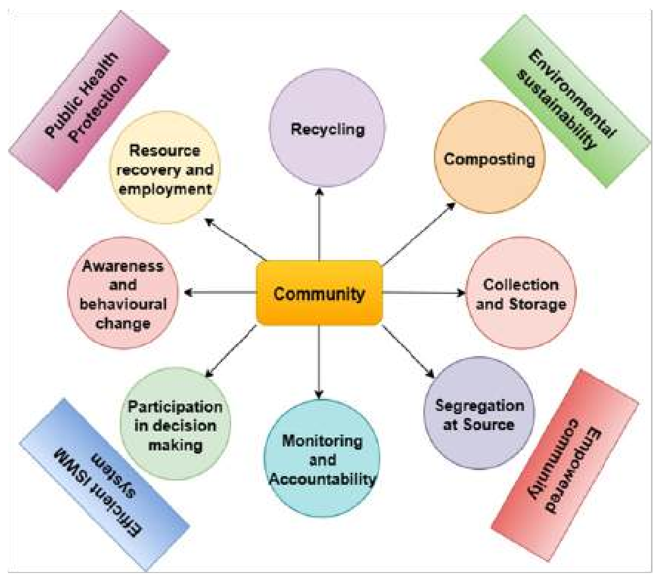

Fig. 1. Role of community in MSW management and its ultimate outcomes

CHALLENGES IN INTEGRATED SOLID WASTE SYSTEM

Lack of Awareness: Awareness among citizens and their participation to segregate waste at source, door-to-door collection, and disposal in appropriate collecting bin is imperative. This awareness plays a crucial role in ISWM and enhances the efficiency of waste management process. It is the most critical step in the whole process of ISWM, which helps in handling the solid waste properly, thereby leading to ultimate success.

Characterization of municipal solid waste: The characterization of the type of waste generated and disposed on landfill is not widely conducted at most of the places. The policy-makers rely on the limited source of information available from few places and are therefore unable to provide appropriate solutions for the kind of waste produced for a particular region, as a result of which, appropriate management process is not being undertaken.

Urbanization and lack of appropriate level funding: With the population growth, and urbanization, a major challenge for an appropriate landfill site selection has become a problem. Inadequate financial support to cater to waste management further aggravates the problem. Due to financial crunch ULBs do not have adequate infrastructures to provide suitable solutions.

Implementation of rules at ground level: Urban Local Bodies do not implement the Municipal Solid Waste Management Rules adequately at the ground level, making it difficult to manage the MSW properly. There is a need to create a dedicated group of skilled staff for ULBs with specialization in MSWM. Adequate training and hands-on experiments would enable them to identify bottlenecks at implementation level and take appropriate actions accordingly.

Failure of waste-to-energy projects: India is still struggling to make waste-to-energy projects successful. There is an urgent need to import economically feasible and proven technologies. Apart from this, suitably characterized and segregated waste needs to be supplied to waste-to-energy plants as per its requirement.

Involvement of organized sector: For improving the efficiency of waste collection and segregation at source, rag-pickers can be engaged through organized sector. However, due to lack of the industries involved in waste recycling and acceptance of society, this vast potential has been ignored.

RECOMMENDATIONS

Community-based SWM in the IHR requires a decentralized, participatory, and context-specific approach that integrates ecological sensitivity, livelihood opportunities, and strong governance. Few approaches that need to be followed are:

•Establish decentralized waste collection, segregation, and processing units at village and town levels to avoid transport challenges due to terrain.

•1Promote small composting pits, small-scale biogas plants, and vermin composting to handle biodegradable waste locally.

•Introduce segregated collection points (eco-bins) along trekking routes, tourist hubs, and rural settlements.

Enhance Community Participation

•Launch awareness drives using local languages and cultural platforms on the environmental and health impacts of poor waste disposal.

•Provide incentives for segregation, composting, and recycling, such as discounts in service charges, free compost for farmers, or recognition programs.

•Involve Resident Welfare Associations (RWAs), women's self-help groups, and youth clubs in waste collection and monitoring.

•Encourage community-based monitoring through NGOs and Panchayats for accountability.

Tourism-Linked Waste Management

•Develop eco-tourism based waste management protocols, such as "Carry-back your waste" rules for trekkers, mandatory segregation in hotels and homestays, and seasonal waste action plans.

•Install eco-bins and collection bins in tourist-heavy zones.

•Levy eco-taxes/waste management fees on tourists, channelled into maintaining local SWM infrastructure.

Capacity Building & Training

•Conduct training programs for village community, women, and youth on segregation, recycling, composting, and safe handling of plastics.

•Build skill development programs in recycling, up-cycling, and waste-to-resource enterprises to generate livelihood opportunities.

•Train ULB staff and volunteers in SWM technologies suited for hilly terrain.

Policy & Governance Support

•Enforce Solid Waste Management Rules with region-specific guidelines for mountain states.

•Integrate Panchayats, municipalities, NGOs, and informal sector workers into a coordinated SWM system.

•Encourage community-owned enterprises for waste collection and recycling, supported by municipal partnerships.

Financial Sustainability

•Adopt public–private–community partnerships (PPCPs) for funding and operational support.

•Implement circular economy approaches, promote recycling hubs, compost sales to farmers, and plastic buy-back schemes.

•Introduce extended producer responsibility (EPR) for packaged goods commonly sold in mountain tourist areas.

Technology & Innovation

•Use region-appropriate WtE solutions (e.g., compact biogas plants, pyrolysis units for plastics, small-scale incinerators for medical waste).

•Introduce digital platforms/mobile apps for reporting waste hotspots, scheduling collection, and incentivizing participation.

•Encourage eco-friendly packaging alternatives through local innovations and support green entrepreneurship.

CONCLUSION

Community-based solid waste management provides a viable and sustainable solution to handle the mounting problem of waste management, particularly in environmentally sensitive regions like the IHR. Active involvement of local communities in the process not only develops a sense of ownership, but also guarantees the application practices that are culturally appropriate, and reduces the burden on government institutions. Besides, the process of waste management can be made more efficient through the integration of traditional knowledge with modern waste management techniques, thereby ensuring environmental sustainability. However, for the long-term success, it is crucial to put consistent efforts, conduct awareness campaigns, capacity-building programs, policy support, and develop strong institutional linkages between communities, local bodies, and government agencies. Through collaboration and sense of shared responsibility, community-driven models can lead the way towards a cleaner, healthier, and more sustainable future. Additionally, adopting decentralized and innovative waste solutions can help in converting the waste into a resource, also supporting the local livelihoods and strengthening resilience against ecological pressures. Community-led waste management can not only safeguard the fragile mountain ecosystems but can also contribute to achieving national and global sustainability goals.

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PROMOTING NATURAL RESOURCES THROUGH ECO-TECHNOLOGICAL INTERVENTIONS: PATHWAYS TO SUSTAINABLE DEVELOPMENT IN THE COLD DESERT OF LADAKH HIMALAYA

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ABSTRACT

The Trans-Himalayan region, encompassing the Karakoram, Ladakh, Zanskar, and Kailash Mountain ranges, places Ladakh at the northernmost frontier of India. Characterized as a cold desert with annual precipitation below 100 mm, Ladakh's unique climate, sociological structure, and ecological conditions present both challenges and opportunities for sustainable development. The region's limited agricultural window (April to September) leaves a significant portion of the year devoid of farming activities, necessitating alternative livelihood sources for local communities, particularly women. This initiative aims to enhance the utilization of locally available yet underutilized natural resources by imparting knowledge and skills through hands-on training, capacity-building workshops, and technology dissemination. The focus is on empowering women by integrating traditional practices with modern innovations to promote sustainability and economic resilience. Skill development programs have been conducted to promote alternative livelihoods, particularly during the non-agricultural period, emphasizing eco-friendly technologies and local entrepreneurship. Over the past five years (2020–2024), the Ladakh Regional Centre has facilitated 36 training programs across diverse ecological zones, Leh Valley, Suru Valley, Nubra Valley, and Changthang Region, engaging 971 participants. These programs encompassed activities such as mushroom cultivation, basket weaving, and the establishment of Sea buckthorn processing units. Furthermore, efforts have been directed towards branding, market linkages, and entrepreneurial support to ensure the sustainability of these initiatives. Notably, the "Strengthening Ladakh's Livelihoods" project, funded by NABARD, has played a pivotal role in enhancing sea buckthorn harvesting and processing as a viable economic activity. The impact of these initiatives extends beyond economic empowerment, fostering entrepreneurship, promoting biodiversity conservation, and preserving traditional knowledge systems. The outcomes demonstrate significant progress in rural sustainability, with trained individuals becoming key drivers of socio-economic transformation in their communities. The integration of scientific assessments, such as the ecological and phytochemical evaluation of sea buckthorn, further reinforces the project's commitment to environmental stewardship and long-term resilience against climate change. Through continued collaboration between local communities, government agencies, and research institutions, this initiative seeks to establish a model framework for sustainable rural development in Ladakh, leveraging natural resources for enhanced livelihood security and ecological balance.

Key words: Sustainable Livelihoods; Women Empowerment; Eco-friendly Technologies; Seabuckthorn; Capacity Building; Rural Development in Ladakh

INTRODUCTION

The Trans-Himalayan Mountain consists of Karakoram, Ladakh, Zaskar and Kailash Mountain ranges in which Ladakh falls under northern most range and extends its boundary from 32° to 36° North and 75° to 80° east having elevation ranges from 2300 to 5000 m above sea level (Hussain *et al.,* 2024; Bhat et al., 2024; Jain *et al.,* 2020). The region comes under cold desert area as it receives less than 100 mm rainfall per year and generally experiences dryness throughout the year due to low relative humidity. In view of complexity and fragility, the Leh, Ladakh region is one of the unexplored areas in terms of biodiversity assessment (Charan *et al.,* 2012; Juyal, 2014; Kumar and Yangchan, 2021). Moreover, Ladakh has an entirely different climate, sociological arrangements, and environmental conditions. In these high altitudes (usually above 3000m asl), due to the harsh weather conditions, the growing season for plants has restricted between April to September which consequently during a year, substantial period has no agricultural activity by the villagers (Angmo and Mishra, 2009; Sarkar and Namgyal, 2019; Namgyal and Sarkar, 2023).However, Ladakh is largely devoid of natural vegetation (referred to as a Cold Desert region), some of the naturalresource plants are available at many places. Local products have been developed on these natural resources initially for self-use but few have seen a path to the commercial market (Bhasin *et al.,* 2023; Sarkar and Namgyal, 2019). Largely these practices are being done to some pockets so the entire landscape has not been benefited and women entrepreneurship has not been developed at large. So, the aim is to blend the available time (due to no agriculture) with village women and utilize the no/less known natural resources in their surroundings through providing knowledge on resources and value addition to the existing products (Clouse, 2020; Murtaza and Romshoo, 2021). At the grass-root level of communities' various options and natural resources exists in the surrounding environment but on many occasions utilization of these resources is not being converted into opportunities through local transformations to promote local and regional sustainability. Conducting the skill development programs focusing on women of the region based on natural resources may play a major role as an alternative livelihood source, especially in the winter months. The project is mainly focused though such a capacity building exercise (Clouse, 2020; Luftu-ul-Hasnaen *et al.,* 2023), women will receive formal training on enhancing their skill and knowledge. The training which they got will be passed to their younger generation and friends. Not only will they learn and enhance their products but will also feel motivated and enthused as they will feel that their skills are valued and appreciated. However, these practices have largely been benefitted the end seller where the local level manufacturers do not get such benefits (Luftu-ul-Hasnaen *et al.,* 2023; Nataraj *et al.,* 2022; Haq *et al.,* 2022). To promote and harvest the potential of natural resources of Ladakh, Rural Technology Demonstration and Training Centre, as an initiative by Central and state Government, have made efforts to promote and disseminate the technology developed in rural areas of Ladakh.Therefore, this initiative aims to capitalize on the non-agricultural period by engaging village women in skill development related to value addition and sustainable utilization of lesser-known natural resources found in their immediate surroundings (Luftu-ul-Hasnaen *et al.,* 2023;Nataraj *et al.,* 2022; Haq *et al.,* 2022). There exists a wide range of natural resources in these areas, but they are seldom transformed into sustainable livelihood opportunities due to lack of knowledge, skills, or institutional support. Skill development programs tailored for women, focused on local biodiversity and resource-based entrepreneurship, could provide meaningful alternate livelihood options, especially during the lean winter months (Valliappa and Kumar, 2022; Jahangir *et al.,* 2022; Angmo, *et al.,* 2022). This project seeks to foster community-based learning where women not only enhance their product-making skills but also transfer this knowledge to younger generations. Empowerment through recognition and value for traditional skills can boost morale and economic independence (Kumar and Yangchan, 2021; Lama and Norphel, 2016). Nevertheless, the benefits of these practices often bypass local producers, favoring end sellers and intermediaries. Recognizing this gap, initiatives such as the Rural Technology Demonstration and Training Centre, established by Central and State Governments, have begun to promote the dissemination of locally developed technologies in rural Ladakh (Shetty and Hans, 2019; MRD, 2022).

The primary objective is to harness the available off-season time of village women by offering hands-on training in skill development and product innovation based on local natural resources. Such sustainable practices have historically ensured equilibrium between human communities and their environment. The strong social cohesion and indigenous knowledge systems have underpinned this sustainability (Banajawadand Adi 2020; Joseph and Said, 2020; Shetty and Hans, 2019). Organic agriculture, which integrates traditional wisdom with modern innovations, supports both ecological integrity and rural livelihoods (Luftu-ul-Hasnaen *et al.,* 2023; Banajawadand Adi 2020).The looming threat of climate change, rural livelihoods based on natural resources are expected to be disproportionately affected. Nonetheless, biodiversity conservation can enhance ecosystem resilience, ensuring that critical ecological functions are sustained even under climate stress (Rani *et al.,* 2025; IPCC, 2022; Sekhar *et al.,* 2024). The warming trends in Ladakh have intensified in recent decades, necessitating adaptive strategies that bolster both species conservation and rural livelihood security (Sekhar *et al.,* 2024). Therefore, locally adapted and nature-based solutions must be encouraged as pathways to resilience and regional sustainability.

STUDY AREA

The Ladakh Himalaya, characterized by its rugged terrain, extreme climatic conditions, and sparse vegetation, presents unique challenges and opportunities for sustainable development. Covering 59,146 km², the region lies between 34° 9'51" N and 77° 35' 5" E, with elevations ranging from Saltoro Kangri (7,742 m / 25,400 ft) to the Indus River (2,550 m / 8,370 ft). This high-altitude cold desert experiences limited precipitation and harsh winters, making agricultural practices difficult yet crucial for livelihoods. Despite these challenges, Ladakh is rich in natural resources, including medicinal plants, seabuckthorn, apricot, and apple orchards, which support local economies. To harness these resources effectively, appropriate technological interventions have been implemented across distinct agroecological zones. Three strategically established field demonstration and training centers reflect the region's diverse environmental conditions:

Suru Valley (3,000 m asl, Kargil district), Nubra Valley (3,048 m asl, Leh district), and Changthang Region (4,500 m asl, Leh district). These sites enable localized trials and adaptations of eco-friendly technologies, ensuring the successful replication of sustainable agricultural methods.

The initiative promotes resource conservation through hands-on training programs, empowering farmers and Women Self Help Groups (SHGs) to adopt improved techniques for crop cultivation, seabuckthorn processing, and organic farming. By integrating traditional knowledge with modern practices, the project fosters economic independence and environmental resilience. In addition, branding and market linkages have strengthened local businesses, enabling Ladakhi products to gain broader commercial recognition. Through continuous expert engagement, interactive learning, and sustainable resource management, this initiative drives long-term socio-economic growth. By leveraging local strengths and biodiversity, Ladakh emerges as a model for eco-friendly development, ensuring that future generations benefit from the harmonious balance between technology and nature (Fig.1).

METHODOLOGY

Before initiating the program, an in-depth rapid rural appraisal survey was carried out all the three regions to identify the priorities and perceptions of local farmers and Women Self Help Group (SHGs) on selected technologies and their interest in receiving sustained training and exposure to the technologies.

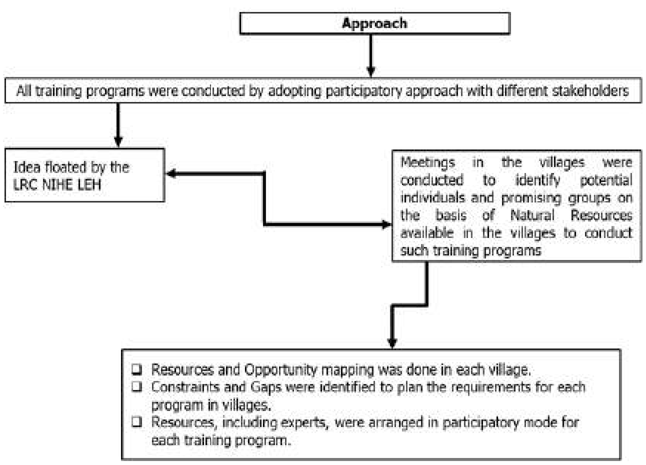

Fig. 1: Participatory Approach to training program and community-centric training program

The primary goal of the aforementioned background is to (i) make use of the time that village women in the Ladakh region have available for purposes other than farming. (ii) Gaining knowledge through practical instruction and value-adding methods to make use of lesser-known locally accessible natural resources in their environment. (iii) Participatory green skill development using an action research approach and awareness for sustainable livelihood. (iv) Developing skills and capacities through live demonstrations and hands-on training to foster entrepreneurship based on local resources. (v) To increase individual capacities and use local resources to generate employment opportunities for off-farm livelihoods.

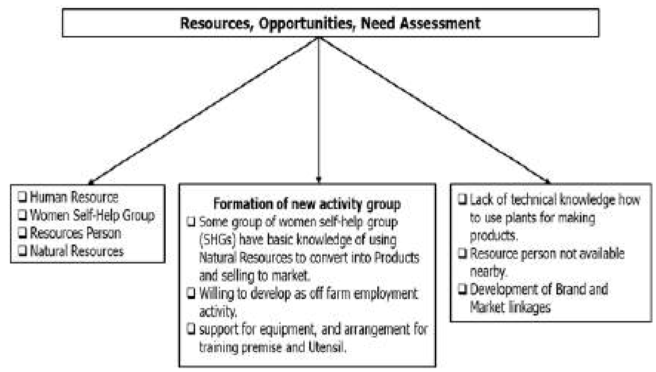

Fig. 2: Empowering the sustainable growth, inclusive strategies for local community development

a) Hands on training on basket weaving.

b) Establishment of Sea buckthorn processing unit and conducting the training program.

c) To establishing branding, and market linkages.

RESULT AND DISCUSSION

Over the past five years (2020–2024), the Ladakh Regional Centre has spearheaded capacity-building programs, fostering socio-economic development among local farmers and Women Self Help Groups (SHGs). A total of 36 training programs were conducted across various villages in three key regions, benefiting 971 individuals (846 females and 125 males). Yearly participation steadily contributed to growth, 183 individuals in 2020 (8 males, 175 females), 409 in 2021 (83 males, 326 females), 139 in 2022 (9 males, 130 females), 134 in 2023 (16 males, 118 females), and 106 in 2024 (9 males, 97 females).The programs encompassed hands-on training in basket weaving, the establishment of a sea buckthorn processing unit in Nubra block, and branding and market linkages to enhance product visibility and ensure sustainable livelihoods. These efforts empowered participants through skill development, enabling economic independence (Table1).

Table 1: Capacity-Building Initiatives conducted by the Ladakh Regional Centre of GBPNIHE in Ladakh (2020–2024)

Year	Total Training	Demonstration	Awareness	Total Village	Male	Female	Total Participant
2020	7	-	1	4	8	175	183
2021	11	8	-	15	83	326	409
2022	8	-	-	8	9	130	139

2023	7	3	-	5	16	118	134
2024	6	-	-	6	9	97	106
Total	39	11	1	38	125	846	971

In addition to skill-building, contact details of farmers and experts were documented to facilitate continuous engagement and consultation. Regular field expert visits ensured that farmers acquired in-depth knowledge of relevant technologies, which were imparted through structured lectures and interactive sessions. Training materials were designed in English and translated into local dialects, making the knowledge transfer accessible to diverse communities.

Beyond immediate training, the initiative focused on long-term sustainability, encouraging farmers to recognize the link between individual and collective behaviors and their livelihoods. Hands-on programs were first trialed at RTC Rural Technology Centre of G.B. Pant Ladakh Regional Centre NIHE Leh before being implemented in villages, ensuring alignment with local natural resource availability. The culmination of these efforts enabled farmers and SHG members to showcase their products at exhibitions and scale up market presence, driving economic growth in the region. The program emphasized collaborative learning, where both experts and farmers strengthened their capacities, paving the way for self-reliance and socio-economic empowerment. Through knowledge-sharing and innovation, these communities transitioned from marginalized positions to active contributors to the local economy.

The course of the reporting period spanning from 2020 to 2024, LRC primary focused wason executing non-farm employment activities through comprehensive skill development programs. These programs specifically targeted village clusters reliant on natural resources for their livelihoods. Our principal aim was to empower participants with the necessary expertise to effectively solve local issues related to livelihoods, and sustainable use of the natural resources. To achieve this goal, we placed a strong emphasis on capacity building and on-site training programs. Our intention was to impart a sufficient level of knowledge and skills to each participant, enabling them to tackle challenges independently. We strived to equip them with the tools and insights required to address local livelihood and natural resource-related problems effectively. An overview of the various skill building programs organized during 2020-2024 is given in Fig. 3. The implementation of above skill development programs and capacity building initiatives in Ladakh has yielded remarkable progress and positive outcomes. A total of 971participants from 25villages actively engaged in the training programs, acquiring valuable skills in their respective domains. Their training encompassed diverse areas such as basket product creation, value addition to apricot-based goods, and development of sea buckthorn products. Efforts were made to establish market linkages for some products, enabling the trained participants to connect with potential buyers and consumers. This facilitated the development of market-ready items and the implementation of marketing strategies to promote the unique features and benefits of these locally made products. The outcomes of these initiatives extend beyond economic empowerment. They have fostered entrepreneurship, encouraged sustainable resource utilization, and promoted the preservation of local traditions and cultural heritage. The trained individuals have become catalysts for positive change in their communities, driving innovation and contributing to the overall well-being of Ladakh's rural landscape. Among these training programs, one of the most notable trainings was on 'Sea buckthorn,

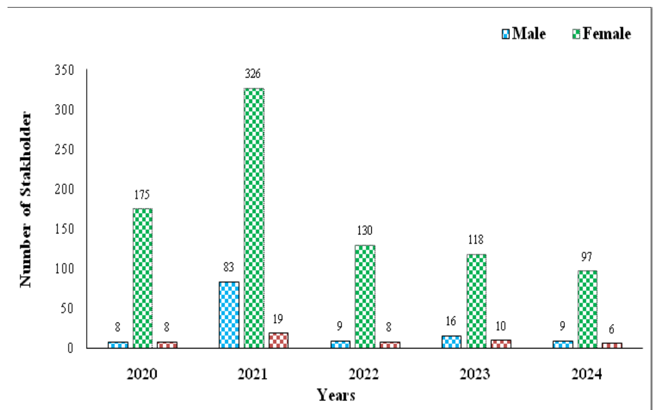

Fig. 3: The year wise, capacity building and training programmes conducted by the Ladakh Regional Centre (LRC), GBP-NIHE, (2020–2024).

LRC has developed and received an externally funded project "Strengthening Ladakh's Livelihoods: Empowering Self-Help Groups (SHGs) through Harvesting and Primary Processing of Sea buckthorn "funded by NABARD Project to facilitate its upscaling.

This project particularly aims to establish a model Self-Help Group (SHG) enterprise dedicated torecognizing the ecological significance and economic potential of sea buckthorn, the proposed proposal seeks to harness the benefits of seabuckthorn in a manner that not only addresses the challenges faced by Ladakh's communities but also promotes sustainable practices and livelihoods. By conducting a comprehensive ecological and phytochemical assessment of sea buckthorn, empowering self-help groups (SHGs) through training and support, and establishing value chains for sea buckthorn products, this project aims to create a win-win situation, enhancing livelihoods while promoting responsible environmental stewardship. Furthermore, by fostering cooperation and knowledge-sharing among local communities, the project intends to leave a lasting impact on the region's resilience in the face of climate change and other challenges. Sea buckthorn harvesting and primary processing, thereby creating an additional income source for its members. The main objective of the project is to conduct an ecological assessment of sea buckthorn berry production within specified unit areas at selected sites. To evaluate the phytochemical and nutraceutical properties of berries at various stages of development to determine the optimal harvesting time for maximizing these properties in the Chamshen village of Nubra valley and Matho village in Leh district.

CONCLUSION

The initiatives in Ladakh from 2020 to 2024 showcase a transformative model for sustainable rural development in fragile high-altitude ecosystems. By leveraging the non-agricultural period and prioritizing women-centric training programs, these efforts have empowered marginalized groups while utilizing underutilized natural resources such as sea buckthorn, apricot, and wild grasses. A decentralized, participatory approach through demonstration centers in Suru, Nubra, and Changthang ensured adaptive solutions. Micro-processing units, live field demonstrations, and market linkages enhanced product value, strengthened economic viability, and preserved traditional knowledge. These interventions fostered resilience against climate variability and socio-economic uncertainties while advancing entrepreneurship and self-reliance. Models like the NABARD-supported sea buckthorn initiative offer replicable solutions for resource-constrained mountain regions. Continued collaboration among communities, policy-makers, research institutions, and development agencies is essential for expanding green skill development and ecological stewardship, ensuring long-term sustainability and climate-resilient economies that respect cultural heritage.

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HIMACHAL PRADESH POLICY ON PLASTIC POLLUTION: A COMPREHENSIVE APPROACH TO SUSTAINABLE PLASTIC WASTE MANAGEMENT

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ABSTRACT

Himachal Pradesh, a Himalayan state renowned for its pristine natural beauty and fragile ecosystem, has been a pioneer in India's fight against plastic pollution. Faced with the dual threats of environmental degradation from unchecked plastic waste and the risks to its vital tourism economy, the state government enacted a progressive and multi-faceted policy framework. This research paper provides a comprehensive analysis of the Himachal Pradesh Policy on Plastic Pollution, tracing its trajectory from the 1995 Non-Biodegradable Garbage (Control) Act to its integration with the national Plastic Waste Management Rules (2016–2022). The study employs a mixed-methods approach, utilizing qualitative review of government notifications, policy documents, and secondary literature, combined with quantitative analysis of data from the Himachal Pradesh Pollution Control Board (HPPCB) and Urban Local Bodies (ULBs). The study examines key policy components, legislative pillars, implementation mechanisms, socio-economic impacts, prohibitions, Extended Producer Responsibility (EPR), promotion of alternatives and spatial challenges across Himachal Pradesh. Findings indicate that while the state has significant achievements, including increase in public awareness, visible reductions in plastic litter, the emergence of green markets, and replication by other Himalayan states. However, profound challenges related to inconsistent enforcement, the availability and cost of alternatives, cross-border plastic waste influx, and inadequate rural infrastructure persist. The paper concludes that Himachal Pradesh's policy offers invaluable lessons in proactive environmental governance but requires continuous adaptation, stronger inter-state collaboration, significant investment in waste processing infrastructure, and a deepened commitment to a circular economy to achieve its goal of sustainable plastic waste management.

Key words: Plastic Pollution, Waste Management, Environmental Policy, Himachal Pradesh.

INTRODUCTION

Around the globe plastic pollution presents one of the most challenging environmental challenges of the Anthropocene epoch. With annual production exceeding 400 million tons and a dismal recycling rate below 10%, plastic waste is present in every ecosystem on Earth (UNEP, 2021). The problem is predominantly important in regions like the Indian Himalayas, where ecology, challenging topography, sensitive environment, and in current scenarios a massive seasonal tourist influx create a perfect storm for waste management intricacies. These regions face heightened risks of soil contamination, water source pollution, and visual blight, which directly threaten biodiversity, public health, and economic stability.

Himachal Pradesh is one of the Indian states settled in the western Himalayas, is most often referred as "Dev Bhoomi" (Land of the Gods). Its economy is intrinsically tied to its natural capital, relying heavily on agriculture, horticulture, and tourism, which alone contributes over 7% to the state's GDP and employs a significant portion of its workforce (Department of Tourism, HP, 2022). However, the very tourism that fuels its economy also poses a severe threat. The visual scourge of plastic litter in valleys and rivers, the choking of drainage systems leading to urban flooding, and the ingestion of plastic by livestock have emerged as direct threats to the state's sustainable future.

This severe problem pushed Himachal Pradesh to emerge as a pioneer in environmental legislation, enacting one of India's earliest and most stringent policies against plastic pollution long before it became a national priority. This paper argues that the Himachal Pradesh Policy on Plastic Pollution has evolved from a simplistic, prohibition oriented ban into a comprehensive, though not unflawed, regulatory framework that increasingly aligns with the principles of sustainable materials management and a circular economy. The policy represents a remarkable case study of environmental federalism, demonstrating how a state can exercise its agency to address a transboundary environmental problem.

METHODOLOGY

This research employs a mixed-methods approach to ensure comprehensive analysis, combining qualitative and quantitative data insights to providea robust understanding of the policy's impact.

Qualitative Analysis:

Document Analysis: Primary policy documents, including the Himachal Pradesh Non-Biodegradable Garbage (Control) Act (1995, with later amendments), notifications from the Department of Environment, Science & Technology, and directives from the HPPCB, were systematically examined. National frameworks such as the Plastic Waste Management Rules (2016, 2018, 2021, 2022) were also analyzed to situate the state's efforts within a broader governance context.

Literature Review: Scholarly research, institutional reports, and media archives (e.g., The Tribune, Himachal Watcher) were reviewed to trace the evolution, implementation challenges, and public perception of the policy.

Quantitative Analysis:

Data Collection: Secondary data were sourced from HPPCB annual reports (2018–2023), CPCB records, and Department of Tourism statistics. Key variables included plastic waste generation, collection and processing volumes, EPR compliance levels, enforcement raids, penalties, and tourist inflows.

Data Interpretation: Basic statistical methods (trend analysis, growth rates) were applied to evaluate policy effectiveness, highlight implementation gaps, and measure enforcement outcomes.

Literature Review:

The discourse on plastic waste management is vast and interdisciplinary. Existing literature can be broadly categorized into several themes relevant to this study.

The Global and National Plastic Problem: Plastic pollution's environmental and health impacts are well-documented. Rochman *et al.,* (2013) highlighted toxicological effects on marine ecosystems, while NITI Aayog (2021) emphasized the vulnerability of Himalayan regions, noting their limited carrying capacity for plastic waste and risks such as soil degradation and clogged drains. Recent research by Bhaduri *et al.,* (2024) on the Beas River basin in Himachal Pradesh identified microplastic contamination in sediment and water, linked to tourism and inadequate wastewater treatment, underscoring the pervasiveness of both macro- and microplastic pollution.

Policy Responses to Plastic Pollution: Literature comparing policy instruments highlights the strengths and limitations of bans versus market-based tools. Nøklebye *et al.,* (2022) argued that bans, though popular, face enforcement challenges and can adversely impact informal vendors. Lindhqvist (2000) concept of EPR is seen as more sustainable by internalizing environmental costs, though Faibil *et al.,* (2022) and others note implementation hurdles in developing economies, including poor monitoring and weak recycling infrastructure. Dwivedy and Mittal (2013) predicted that consumer acceptance and cost-effective alternatives would determine the success of policies—an observation particularly relevant for Himachal Pradesh.

Waste Management in Mountainous Regions: Scholars such as Kumar *et al.,* (2017) highlighted the "exporter dilemma," where tourism-driven waste exceeds local capacity. They emphasized decentralized systems and smaller Material Recovery Facilities as more viable than centralized plants due to difficult terrain and high costs. Dulta (2024), focusing on Shimla, identified a persistent gap between waste generation and treatment capacity, exacerbated by tourist inflow.

Studies on Himachal Pradesh's Policy: Research on HP's plastic ban is limited but growing. Rakesh (2019) noted high awareness but weak enforcement of the 2003 ban. Thakur *et al.,* (2021) found public support in Solan but frustration with inadequate alternatives. Building on these insights, this study evaluates Himachal Pradesh's policy evolution, enforcement, and outcomes in the broader context of sustainable waste management in fragile Himalayan ecosystems.

HISTORICAL CONTEXT AND EVOLUTION OF THE POLICY

Himachal Pradesh's journey against plastic pollution is a story of progressive escalation and adaptation, often placing the state ahead of the national curve. Its policy framework did not emerge in a vacuum but developed as a direct response to visible and growing environmental crises in the fragile Himalayan ecosystem, including cattle deaths from plastic ingestion, the clogging of drains during monsoon seasons, and littering in tourist hotspots.

The Foundational Phase (1995–2005): The Himachal Pradesh Non-Biodegradable Garbage (Control) Act, 1995 marked the state's first major legislative intervention against plastic pollution, creating a legal framework to regulate, restrict, and prohibit the use, storage, and distribution of non-biodegradable waste, including plastics. In 1999, Himachal Pradesh became the first state in India to ban plastic carry bags below 20 microns in thickness, a pioneering measure that laid the foundation for a culture of refusal toward single-use plastics. Mounting public and political concern—particularly over cattle deaths caused by ingesting polythene and the clogging of drains during monsoons—provided the immediate impetus. Building on this, the state strengthened its stance in 2003 by amending the rules to mandate a much higher minimum thickness of 70 microns, going well beyond the national standard. This was a radical step for its time, signaling the government's determination to address plastic pollution more aggressively and positioning Himachal Pradesh as a frontrunner in environmental governance.

Strengthening the Ban (2009–2013): Recognizing loopholes and weak compliance, the state amended the 1995 Act in 2009, strengthening the regulatory framework and expanding penalties, including provisions for imprisonment. During this period, the government progressively restricted thinner plastic bags below 30 microns to comply with national standards and in 2011 went further by banning all plastic carry bags, irrespective of thickness. This represented a philosophical shift—from regulating problematic products to outright elimination. By 2013, it was extended to include thermocol cutlery (cups, plates, and glasses).

Integration with the National Framework (2016–Present): The introduction of the Plastic Waste Management (PWM) Rules, 2016 by the Government of India provided a more comprehensive and structured framework for plastic regulation across the country. For Himachal Pradesh, these rules reinforced its earlier prohibitions while introducing new mechanisms such as EPR, which shifted accountability to producers for the collection and recycling of plastic waste. The state was compelled to integrate its bans into a larger waste management architecture, moving from a standalone prohibitionist model to a life-cycle approach that combined prevention, reduction, and management.

The national ban on 19 identified Single-Use Plastic (SUP) items in 2021–2022 further strengthened Himachal Pradesh's regulatory standing, particularly by addressing the challenge of cross-border inflow of banned plastics from neighbouring states. In this phase, Himachal's policy matured into part of a broader national movement while continuing to enforce its own stringent and pioneering measures. This evolution represents a clear learning process: beginning with targeting the most visible and harmful products, then moving towards holistic integration of waste prevention and management strategies that recognize the shared responsibility of governments, producers, and consumers alike.

Table 1: Historical Context and Evolution of the Policy

Year	Act/Notification	Key Provisions
1995	Himachal Pradesh Non-Biodegradable Garbage (Control)	Legal framework to regulate non-biodegradable waste, including plastics.
1999	State Notification	Ban on plastic carry bags below 20 microns.
2003	State Notification	Strengthened restrictions to bags below 70 microns.
2009	Amendment to 1995 Act	Empowered authorities, expanded penalties, included imprisonment.
2011	Cabinet Approval & Notification	Total ban on plastic carry bags of any thickness; prohibition extended to plastic cups and plates.
2013	State Notification	Ban on thermocol cutlery (cups, plates, glasses).
2016	Adoption of PWM Rules, 20	Integrated EPR, segregation, and recycling mandates.
2018	State Notification	Ban extended to more single-use plastics (cups, glasses, straws, packaging).
2021–22	PWM Amendment Rules & State Action	Ban on 19 SUP items; strict monitoring and promotion of cloth/jute bags.

Source: HPCB

KEY COMPONENTS OF THE POLICY FRAMEWORK

The HP policy is not a monolithic law, but a composite framework built on several interconnected pillars, each addressing a different part of the plastic pollution life cycle.

The Prohibitory Regime (Bans): The most visible and well-known aspect of the policy is the prohibition on the manufacture, import, storage, sale, and use of specific plastic items. The current banned list is comprehensive and includes:

All plastic carry bags (regardless of thickness)

Single-use plastic items like cups, plates, spoons, forks, straws, and stirrers

Thermocol items for decoration.

Plastic wrap/packaging for sweet boxes

These bans have positioned Himachal as one of the strictest states in the country on plastic regulation.

Extended Producer Responsibility (EPR): Beyond bans, the state aligns with the Plastic Waste Management Rules, 2016, which mandate EPR. Producers, Importers, and Brand Owners must take responsibility for managing plastic packaging introduced into the market. This is enforced through registration and annual collection targets. In 2022–23, over 29,000 metric tonnes of plastic waste were collected and processed under EPR obligations (HPPCB, 2023), demonstrating the operational strength of this mechanism.

Promotion of Alternatives: Recognizing that prohibitions are ineffective without substitutes, the policy actively promotes eco-friendly alternatives such as cloth, jute, and paper bags. Certified compostable plastics conforming to IS/ISO:17088 standards are also encouraged, although cost barriers and composting infrastructure remain challenges. Incentives for innovation in sustainable packaging aim to strengthen this pillar

Waste Management Infrastructure: A parallel focus is on building waste management infrastructure. Segregation at source into biodegradable, non-biodegradable, and hazardous waste is mandated, while Material Recovery Facilities (MRFs) ensure recyclables are sorted. Non-recyclables are directed towards co-processing in cement kilns, with plants such as ACC Gagal and Ambuja Darlaghat as key partners.

Public Awareness and Participation: Finally, the policy emphasizes public engagement as a cornerstone. Awareness campaigns in schools, eco-clubs, and tourist destinations, along with collaborations with NGOs and civil society, have created broad-based participation. Clean-up drives and signage in tourist hubs ensure that enforcement is supported by grassroots-level buy-in, making the policy more sustainable.

IMPLEMENTATION AND ENFORCEMENT MECHANISMS

The effectiveness of Himachal Pradesh's plastic policy hinges on a robust, multi-tiered implementation architecture that involves coordination among various agencies and a suite of enforcement tools.

Institutional Framework: A multi-agency structure ensures wide-reaching and effective implementation. HPPCB serves as the central nodal body, responsible for overall monitoring, guiding ULBs and coordinating with the CPCB on EPR compliance. Local governance structures such as Municipal Corporations and Nagar Panchayats enforce policy at the ground level—overseeing door-to-door waste collection, segregation, processing, and enforcing bans. In rural regions, Gram Panchayats shoulder similar responsibilities, although their capacity is often limited by resource constraints. Strategic direction and state wide awareness campaigns are managed by the Department of Environment, Science & Technology in conjunction with the HPPCB. Enforcement is further supported by the police, who aid in joint raids and manage interstate checkpoints to intercept the inflow of banned plastic items.

Monitoring and Penal Mechanisms: Himachal Pradesh uses a multi-pronged enforcement strategy. Joint inspection team comprising officials from ULBs, HPPCB, and law enforcement conduct raids on shops, markets, and warehouses. Additionally, online challan systems allow for efficient imposition and payment of fines Per the Act and subsequent notifications:

•Fines range from Rs. 500 for up to 100 g of seized SUP, scaling to Rs. 25,000 for quantities above 10 kg.

•Littering penalties: Rs. 1,000 for individuals and Rs. 5,000 for institutions or commercial entities

•The 1995 Act itself prescribes penalties of up to Rs. 25,000 in fines or up to three months' imprisonment for first-time offences, doubling in case of repeat violations

A critical yet resource-intensive component is the operation of checkpoints at key interstate borders. These checkpoints aim to stem the cross-border flow of banned plastics, a persistent and significant challenge to the policy's integrity.

ANALYSIS OF IMPACT: DATA, SUCCESSES, AND CHALLENGES

Quantitative Data and Trends: The following table summarizes key data points from the last five years, illustrating the scale of the challenge and the state's response:

Table 2: Key Metrics for Plastic Waste Management in Himachal Pradesh (2018-2025)

Year	Plastic Buy-Back Quantity	Amount Paid (Rs.)	Plastic Roads Constructed (km)	Fines Collected (Rs.)
2018-19	Not specified	Not specified	Not specified	Rs. 20 lakh (approx.)
2019-20	1,054 kg	Rs. 49,125	5.53 t used in road; 38.6 t sent as RDF to cement plants.	Rs. 13.50 lakh (from 1,603 violators)
2023-24	20,902 kg	Rs.75/kg purchase rate	112 km of plastic roads	Rs. 10.24 lakh (from 1,138 violators)
2024-25	29,385.10 kg	Rs.13.04 lakh total	Not specified	Rs. 11.80 lakh (from 907 violators)
2025 (up to mid-year)	~275,000 kg over three years	Purchase rates: Rs.35/kg shredded, Rs.15/kg un-shredded	227 km roads completed (with more planned)	Not specified

SUCCESSES AND POSITIVE OUTCOMES

High Public Awareness: The policy has been tremendously successful in raising consciousness. A 2022 survey by the Department of Environment indicated that over 85% of respondents in urban areas were aware of the ban and its specifics.

Visible Reduction in Litter: There is a noticeable reduction in the most visible forms of plastic litter straws, cups, and thin bags in major tourist towns, parks, and along key highways.

Behavioral Change: A significant segment of the local population has adopted reusable bags. It is now common to see shoppers in markets carrying their own cloth bags. Many retailers have switched to paper or cloth packaging voluntarily.

Spurring a Green Market: The ban has created economic opportunities. Local enterprises manufacturing paper bags, cloth bags, and areca-leaf plates have emerged. This aligns with the goal of creating a circular economy and local livelihoods.

Leadership and Replication: HP's model has been studied and partially replicated by other states like Uttarakhand and Jammu & Kashmir, establishing it as a leader in Himalayan environmental governance. It demonstrates that sub-national entities can take bold, proactive action.

PERSISTENT AND EMERGING CHALLENGES:

Himachal Pradesh's plastic policy, while ambitious, is significantly constrained by a complex web of deep-rooted and interconnected challenges that threaten its long-term efficacy and environmental goals.

Inconsistent and Selective Enforcement: Enforcement is strong in urban cores (e.g., Shimla's Mall Road) but weak in peri-urban areas, smaller towns, and rural markets. It often targets small, visible vendors (e.g., fruit sellers) while violations by larger establishments or wholesale suppliers can go unchecked. The number of enforcement personnel is insufficient for the vast territory. This creates a perception of unfairness and reduces the policy's legitimacy.

The Cost and Performance of Alternatives: This remains the biggest practical hurdle. A paper bag can cost 3-5 times more than a plastic bag. For a small vendor operating on thin margins, this cost is prohibitive and is often passed on to the consumer, creating resistance. Furthermore, alternatives like paper are not always durable, especially in HP's rainy season, and cloth bags have hygiene issues for carrying wet items like meat and fish.

Cross-Border Influx: This is a major structural loophole that undermines the entire policy. Banned items are easily and cheaply available in neighboring states like Punjab, Haryana, and Uttarakhand. Consumers and traders near border towns, routinely bring in plastic bags from outside. Seizing this at a few checkpoints is an almost impossible task. This creates a frustrating scenario where law-abiding shopkeepers in the state's interior are at a competitive disadvantage compared to those near borders.

Inadequate and Uneven Waste Infrastructure: This is the critical Achilles' heel of the entire policy. The implementation system has not kept pace with the legislative ambition.Even, the state capital, Shimla, with a floating population that often doubles its permanent residents, struggles with a frequently malfunctioning processing plant and poor waste segregation, often resorting to dumping. Tourist hubs like Manali are completely overwhelmed during peak seasons, leading to informal dumping on riverbanks, a issue flagged by the Himachal Pradesh High Court. The challenging topography of areas like Dharamshala makes comprehensive collection exceptionally difficult and costly.

Green washing and Ambiguity: The market is flooded with "biodegradable" plastics that do not meet standards and require specific industrial composting conditions not available in HP. This confuses consumers and authorities, allowing banned plastics to re-enter the market under a green label. There is a lack of cheap and rapid testing facilities to verify claims of composability.

Limited Rural Outreach: The policy's reach in HP's vast rural landscape is minimal. Waste collection is sporadic, and awareness is lower. The common practice of open burning of plastic waste, including agricultural mulch films, releases toxic dioxins and furans, creating a significant health hazard and contributing to air pollution in the mountains.

CONCLUSION AND RECOMMENDATIONS

Himachal Pradesh's ambitious policy on plastic pollution stands as a testament to strong political will and has positioned the state as a leader in environmental governance. It has successfully catalyzed public awareness, reduced the most visible forms of litter, and spurred local innovation in alternatives. Despite these significant achievements, a thorough analysis reveals that the policy's effectiveness is constrained by a set of persistent, systemic challenges that create a gap between legislative intent and on-ground execution.

The most pressing constraints include inconsistent enforcement that undermines the policy's fairness, the prohibitive cost of alternatives that hinders widespread compliance, and rampant cross-border leakage of banned items from neighboring states with weaker regulations. Perhaps the most critical limitation is that the state's waste management infrastructure has failed to keep pace with the policy's ambitions. This is especially evident in the state's booming tourist destinations and under-resourced rural areas, where waste collection and processing systems are often overwhelmed.

To bridge this implementation gap and fully realize its vision of a circular economy, the policy must evolve through targeted, evidence-based upgrades. First, enforcement must be strengthened and modernized through technology, such as a dedicated citizen complaint app with GPS tagging and focused on interstate entry points. Second, alternatives must be made affordable through targeted subsidies for local manufacturers and bulk procurement by urban local bodies. Third, and crucially, the state must lead the formation of an inter-state council with Punjab, Haryana, and Uttarakhand to harmonize banned items and enforcement protocols, thereby creating a larger regulated market and eliminating the incentive for cross-border shopping.

Concurrently, massive investment is required in decentralized waste infrastructure, including Material Recovery Facilities (MRFs) and composting units tailored to the state's hilly topography. The EPR framework must also be deepened to encourage product redesign and formally integrate into the informal waste sector. By addressing these implementation challenges with the same boldness that launched the initial ban, Himachal Pradesh can transform its policy from a remarkable experiment into a truly sustainable and replicable model for mountain regions worldwide. The health of its pristine environment and the sustainability of its ecosystem depend on this continued evolution.

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CULTIVATION OF AGARICUS BISPORUS THROUGH LOW-COST COMPOSTING TECHNOLOGY: AN IMPORTANT APPROACH FOR LIVELIHOOD IMPROVEMENT

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ABSTRACT

Fungi play significant role in maintenance and development of sustainable environment as well as the forestry and agriculture. Microbial community helps in maintaining the ecosystem services. In soil, these microbial communities like fungi, bacteria, actinomycetes are responsible for controlling and acceleration the cycling of nutrients and availability of these nutrients. *Agaricus biosporus*, is an edible saprophytic fungus from Basidiomycetes. The present study is a part of dissertation project which was carried out in the Department of Botany, Doon (PG) College of Agriculture, Science and Technology, Camp Road, Selaqui, Dehradun (Uttarakhand), during the month of December to March 2022-2023. The pure culture and wheat grain spawn of *Agaricus bisporus* was obtained from Mushroom Research and Training Centre, G.B Pant university of Agriculture and Technology, Pantnagar (Uttarakhand). This study illustrates the cultivation of Agaricus biosporus through low-cost composting technology which could be an important approach for future study for sustainability and livelihood.

INTRODUCTION

Microorganisms are the essentialelement on earth. The ubiquity of microbes is just because of their population size rather than any inherent property (Fenchel and Finlay, 2004). As the environmental requirement of microbes are met, they can be found everywhere (Brock, 1961).There are about 75,000 species of soil fungi in the world (Finlay, 2007). The contribution of various classes like Ascomycetes and Zygomycetes and Basidiomycetes shows the depth-specific distribution. The number of fungi is generally found higher in the upper depth of soil. It has been revealed that Himalayan Forest has been converted into degraded lands due to anthropogenic pressures like deforestation, lopping, scraping and trampling leading to continuous loss of soil (Akash *et al.,* 2018,19). Himalayan soil has various nutrients due to degrading activities of the litter by microorganism so it is best suited for the high production rate and sustainability (Akash *et al.,* 2020a,b). Due to the degradation of litter, the soil of this region is rich in nutrients, which is helpful for plants growing around the Himalayan region (Akash *et al.,* 2020b) and also for the survival of microorganism (Akash *et al.,* 2022).

Mushroom is a saprophytic fungus that grows on dead and decaying organic matter. Due to the absence of chlorophyll, it is unable to synthesize its own food and hence is dependent upon the organic matter/substrate for food. However, they have the ability to convert the complex lingo cellulosic waste material into soluble absorbable substances for their nourishment. The mycelia of mushroom perform this job by producing extra cellular enzymes which digest the complex carbohydrate, lignin, lipids and proteins into a form of simple molecules that are easily absorbed by them. Mushroom have fascinated human since ancient time and the consumption and its importance in nutritional and medicinal value have been seen from ancient period like Vedas and Bible (Butler and Bisby (1960). Mushroom are recognized as the alternate source of good quality of protein and these are capable to produce highest quantity of protein per unit area and time from worthless Agro- wastes. These are also good source of vitamins and minerals with certain medicinal properties. In today's world the production of mushroom has become very much important among biotechnical practices all over the world with different methodology as suited with the place and the mushroom species. Mushrooms are recognized as staple food in the diet of some cultures, they are usually considered for their flavour, nutritional, medicinal and condiment value. These are good source of protein which contains all the amino acid necessary for human nutrition, vitamins particularly vitamins C and vitamins B complex, minerals, fats and carbohydrates etc. (Table-1).

Table 1: Nutrient value of mushrooms

PROTEINS	20 – 30 %
FATS	2 – 8 %
CARBOHYDRATES	16 – 85 g / 100 g
VITAMINS	0.32 – 0.65 mg/ g (b_{12})

Agaricus bisporus is and edible basidiomycete mushroom native to grasslands in Europe and North America. With the technical advancement during the past few decades, the cultivation of this species has spread all over the world. When immature and white, this mushroom may be known as common mushroom, button mushroom, white mushroom, cultivated mushroom, table mushroom, and champignon mushroom. When immature and brown, this mushroom may be known variously as Swiss brown mushroom, Roman brown mushroom, Italian brown mushroom, cremini or crimini mushroom, brown cap mushroom, or chestnut mushrooms. The button mushroom is one of the most popular edible fungi contributing more than 32% of total world production (Chang, 1999). Today China is the largest producer of mushroom in the world with 70% of world production happening in China in which white button mushroom is mostly grown seasonally. In India majority of the commercial units are growing A. bisporus for sale in domestic and international market. Today India produces total 4000 ton of mushroom in which A. bisporus contributes about 80-85% of the total annual production. Button mushroom is presently being cultivated by seasonal growers at prevailing room temperature on compost. Compost is most important part of button mushroom cultivation which can be prepared by two i.e. long method and short method of compost preparation.

Mushrooms like other plants are also attacked by pest and pathogens which results in the crop failure. Many pathogens and competitor moulds have been recorded as occurring from time to time on mushroom beds. In India, from the bed of A. bisporus the occurrence of such undesirable fungi like Truffles, Green moulds, Dry bubble, Wet bubble, Ink caps, have been reported to cause extensive damage and reduce yields. Most of the harmful fungi are encountered in compost and casing soil during the cultivation of button mushroom because a majority of small and satellite growers cultivate the button mushroom on unpasteurized compost without proper environmental management, sanitation which result in outbreak of biotic and abiotic disorders. Keeping above in view, the present investigation was undertaken with various objectives and entitled as "The Cultivation of *Agaricus bisporus* through Low Cost Cultivation Technology".

- To prepare compost through long method of composting (L M C) for cultivation of *Agaricus bisporus*.
- To cultivate *Agaricus bisporus* (button mushroom) through low cost cultivation technology.
- To study common diseases which encounter during the cultivation of button mushroom.
- To spread the general awareness among rural community about the importance of mushroom rich in all dietary components, their medicinal value and potential of cultivating them with minimum financial input and facilities.
- To help creating new employment opportunities for the rural community especially farmers/youth/house wives and making them entrepreneurs which will help in generating income.

Table 2: Temperature requirement for optimum growth of A. *bisporus*

MUSHROOM	GROWTH STAGE	TEMPERA-TURE	SOURCE
A. *bisporus*	Mycelia growth	26.7	Dugger (1905)
		25	Lambert (1938)
	Spawn growth	20-25	Edward (1978)
	Fructification	20-22	Edward (1978)
		16-18	Sohi (1988)

RELATIVE HUMIDITY

High relative humidity is favorable for growing all mushrooms. It also prevents drying up of compost and substrate surfaces. Sohi (1988) has suggested maintaining 80-90 per cent relative humidity with moisture content of 62-63 percent (in plastic bag method) and 65-67 per cent (in tray method) in compost for button mushroom cultivation.

CARBON DIOXIDE

It is commonly said that mushroom needs no fresh air during spawn growth. That is not true because accumulation of CO2 only up to 4 percent appears to be beneficial for the mycelia growth of *Agaricus bisporus*(Edward, 1978). The concentration of CO2 must be under 0.08 per cent for fruit body initiation of button mushroom and that even less (0.05 per cent) in certain strains. Low CO2 (not beyond 0.15 per cent) has been found as critical factor for obtaining good yield (Sohi, 1988). Further, it is evident that 0.3-0.5 per cent CO2 in the air above the casing soil results elongation of stipes and inhibition of sporophores initiation.

IMPACT OF CLIMATIC FACTORS

Two distinguishing phases in the growth and development of cultivated mushrooms are the vegetative phase and the reproductive phase. During the vegetative phase enzymes secreted from the mycelium break down the lignocellulosic components into simpler soluble organic compounds, which are absorbed by the hyphae and used for metabolic reaction of the fungus for establishment. When the mycelia are established, they become ready to pass from vegetative phase to reproductive phase, and to provide strong physical support to the fruit body. Certain climatic factors trigger this change from the vegetative stage to reproductive stage. Amongst the factors, temperature, light and changes in atmospheric gases are significant in the transition from the mycelia state to reproductive (fruit body) state (Chang and Miles, 1997). Higher carbon dioxide concentration and temperature are required for the vegetative growth of mushroom while higher oxygen and more light are essential for fruit body initiation.

MATERIAL AND METHODS

This dissertation project was carried out in the Department of Botany, Doon (PG) College Of Agriculture, Science and Technology, Camp Road, Selaqui, Dehradun (Uttarakhand), during the month of December to March 2017. The pure culture and wheat grain spawn of Agaricus bisporus was obtained from Mushroom Research And Training Centre, G.B Pant university of Agriculture and Technology, Pantnagar (Uttarakhand).

The materials used and methods applied are given below:-

1. Mushroom house or shed (partition into two halves for spawn running and mushroom production separately)
2. Substrate store house or shed
3. Water supply
4. Wooden, bamboo or steel racks
5. Sprayer
6. Gunny bags
7. Polypropylene bags (24” ×16”)
8. Polythene sheet (transparent)
9. Substrates viz. wheat straw, wheat grain
10. Spawn, planting spawn
11. Sand
12. FYM (farm yard manure)
13. Agricultural soil
14. Newspaper
15. Fungicides: Carbendazim (Bavistin)
16. Disinfectant: Formalin

PREPARATION OF SPAWN

Generally, spawn preparation is done in two steps, mother spawn and planting spawn, with the use of same medium or different media. Various kinds of spawn media are successfully used in different laboratories. Here, spawn prepared with wheat grain medium is described due to its suitability in respect of its easy availability, low price and efficiency to give equally good production of fruit bodies.

Mother Spawn

Two kg fresh wheat grains were boiled in double volume of water for 25-30 minutes in a pressure cooker. After boiling, the wheat grains were placed in a small bamboo made basket keeping that on a sink for overnight to drain out the excess water and to dry the surface area to minimize stickiness. Sixty grams of calcium Sulphate (gypsum), twenty grams of calcium carbonate and 500 mg Chloramphenicol were mixed separately in a glass bowl and added to the boiled wheat grain on a clean platform with thorough mixing. The mixed substrates (spawn medium) and were filled up in 500 ml milk bottles or conical flasks @ 250 g/bottle. These bottles were plugged with non-absorbent cotton plug and the mouth was wrapped with a piece of brown paper and rubber band. The bottles were now sterilized in autoclave at 15 p.s.i. for 2 hrs. After sterilization on the next day, the spawn medium was inoculated, aseptically, with bit of mycelium colony, taking out from mushroom culture grown in slant or in Petri plate medium*. The inoculated spawn bottles were incubated for 10 days at a suitable optimum temperature in B O D incubator. They were shook twice beating them on hand palm on 3rd and 7th days for even growth of mycelia and to observe contamination if any.

Planting spawn

In this type of spawn, substrate may remain same as in mother spawn or it may be prepared by mixing the boiled grains with half dose of calcium carbonate (5%) and Calcium Sulphate (15%). However, unlike mother spawn, addition of Chloramphenolic was not needed in any kind of the substrate mixture. The packets were plugged with non-absorbent cotton plug supported by an autoclavable plastic or metallic ring. Very old mother spawn was not suitable due to hardness in breaking that with a glass rod. The incubation was done at the room temperature in culture room or at 25 ± 1 °C in B O D incubator, as a suitable. The spawn becomes ready after 14-21 days of growth (Plate I).

Plate I: Sub culturing, spawn preparation and inoculation on wheat substrates of *Agaricus bisporus*

COMPOST PREPARATION

There are mainly two different methods of compost preparation. First one is long method which does not require pasteurization, and the second one is short method where pasteurization is needed. These methods provide adequate levels of nutrients to support the growth of button mushroom. However, of the two methods, the second one is much effective to produce quality compost. In long method the mushroom gives low yield and even in some case crop failure may occur. Various materials in different formulations are used for compost of white button mushroom. However, the ingredients which are required for compost preparation are broadly classified into three major groups as follows:

INGREDIENTS

Base material: Straws of different agricultural products, like wheat, rice, oat, maize stalk, sugarcane bagasse etc. are in this group. The straws are needed to cut into 5-8 cm long pieces in order to create compactness in compost heap.

Supplements: Different types of nutrients are added to the base material to enrich nutritive contents in the compost. The supplements are described as follows:

Manure: It is used to supply nitrogenous material. Chicken manure, horse manure, pig manure and sheep manure are used in compost preparation. Horse manure is the best material for compost preparation, but it is not available everywhere so chicken manure is used mostly. Chicken manure is most suited in short-term composting system, while cattle manure, on the other hand, is not suitable for compost preparation in any system of composting (Vijay and Gupta, 1995).

Carbohydrate nutrient: Different types of materials, such as molasses, malt sprouts, potato wastes, etc are used to supply carbohydrate nutrients in the compost.

Nitrogenous fertilizers: Nitrogenous fertilizer, like ammonium sulphate, calcium ammonium nitrate and urea to enhance microbial growth during composting.

Concentrate meals: Animal feed, like rice bran, wheat bran, cotton seed meals, soybean cake, mustard cake, brewer's grain, are used as supplements to the base material. They are used to provide both nitrogenous and carbohydrate foods.

Rectifying materials: Different types of other materials are also required to rectify the compost. Gypsum and carbonate are used to maintain compost pH and to devoid greasiness/ stickiness of the compost. Insecticides and nematicides are used to control pest attacks.

Formulations: As a result of prolonged research on clues to specific nutritional requirements by an organism, a number of synthetic formulae have been proposed. Among those formula, Solan formula (Table-3) of compost preparation was selected for present project work.

The fruiting stage in mushroom is extremely sensitive to the environment of the room. It is initiated by an abrupt change in the environment conditions. The entire room is ventilated with plenty of fresh air and the room temperature is brought down to 15-18 °C. The spawn running, pinhead formation and fruiting bodies formation are three important phases in the cultivation of mushroom which require proper humidity and temperature.

Spawn Run: It is evident from (Table- 4) that spawn running took 23- 27 days the mycelium completely penetrated the compost and white patches were seen on the surface of the compost (Plate: V). At this stage beds were covered with the casing soil. The object of this stage consists in causing mushroom mycelium to grow as quickly as possible through the compost. After spawning, growing conditions was maintained at the optimum level and uniform as possible inside the spawning room. The room should be maintained at 25 °C or near about.

Pin head: The pinheads formation is the second stage of mycelial growth during cultivation of mushroom. As evident from (Table: 4), the pin heads were observed at earliest within 15-20 days from casing (Plate: VI). The pinhead stage is also a stage of rest. The pinhead stage was completed when pinheads reach a diameter of 3-5 mm, approximately 5-7 days after their initiation. After completion of 'pinhead' formation stage, further growth take place only in air, and the climate conditions in the cropping room should be kept constant as possible. If the temperature is kept at 18 °C, the development of fruiting body is accelerated, where as lower temperature tends to slow it. As evident from (Table- 4), there was a marked increase in temperature in the month of February (25° C), and due to this reason there was slight decrease in pin head formation and yield. (Plate: VII). According to Lambert (1938) a pin head with a diameter of 2 mm will develop fully in 22 days at 10 °C, 10 days at 15.5°C and 6 days at 21.1 °C. However, temperature above 20 °C reduces the yield which is in total agreement with the present Project. Maximum fruiting takes place between 12- 18 °C.

Fruiting bodies formation: This is the third and final stage during the cultivation of mushroom. It took approx. 5-7 days from the time a mushroom first appeared until the fruit-bodies attain the maximum weight and size and become ready for (Table- 4), (Plate: VII). Mushroom continues to develop for about 6-8 weeks. They usually appear in sudden 'flushes' at intervals of about a week and are followed by periods with only a few mushroom appearing in the beds. Usually additional water is applied to the surface of the bed at the time each flush appears. The casing soil moisture must be maintained at a rather high level to obtain maximum yields. Picking: Mushrooms were picked just before the cap expands and the gills are exposed (Plate: VII). At this stage the cap measure 2.5-8 cm across. The mushroom are picked by holding the cap in finger-tips slightly pressed against the soil, and gently twisting and pulling simultaneously till they get loosened from the soil and the mycelia threads binding it to the soil are snapped. The soil particles and mycelia threads clinging to the base of the stack are chopped off. Another practice is to chopp off the stem as close to soil surface as possible. After the mushroom or clump of mushroom has been picked, the remaining fleshy tissue of the stalk is carefully removed from the soil and these holes plugged with fresh sterilized casing soil. With a little experience, the dead mushrooms were easily distinguished from the healthy buttons and were removed from the bed to prevent spread of decay.

Yield of *Agaricus bisporus*: The crop of button mushroom was cultivated by two methods i.e. cultivation in shelves and cultivation in bags (Plate: VII). Cultivation in bags was found less economical as compared to cultivation in shelves. Bags are capable of holding about 25 kg of compost, more if light and less if heavy. With bags on floor only, a building can hold about half as much compost as it would using the tray or shelves. The yields are highly variable and depend on the quality of the compost as on the proper crop management. As for present Project long method of composting was used and the yield in mushroom bed was 2-3 kg/m2, which was little bit low yield. Flegg and Randle (1980) have stated that with appropriate composting, 1 tons of dry straw equivalent of 2.5 tonnes of compost, gives an average yield of 450 kg fresh mushrooms. Yield in bag cultivation was found more as compared to shelves (Plate: VII). It can be due to the temperature of bed. The temperature rises particularly when compost beds are thick, and this leads to the development of fruit-bodies later only at the edges of the bed (Plate: VII, B). This problem can be dealt with two ways: by providing thinner compost beds, and by lowering the room temperature.

Table 3: Average Temperature (^{0}C) of different months during the course of study

MONTH	TEMPERATURE (^{o}C)		
	MAX.	MIN.	AV.
December	22	9	19
	25	15	20
February	27	21	25
March	31	24	28

Table 4: Total days taken during the different growth stage

GROWTH STAGE	DAYS TAKEN
Mycelia growth	23-27
Pin head formation	15-20 days (After casing)
Fruiting body formation	5-7 days (After pinhead)

Plate II: Compost preparation

Plate III: Compost preparation and composting in Shelves (A-G) and in Bags (H-J)

Plate IV: Spawning (A-F)

Plate VI: Watering (A) and Pin head formation (B-F)

Plate V: Casing soil preparation and casing mycelial growth (spawn run-A), Casing soil preparationB-D) and Casing (E,F)

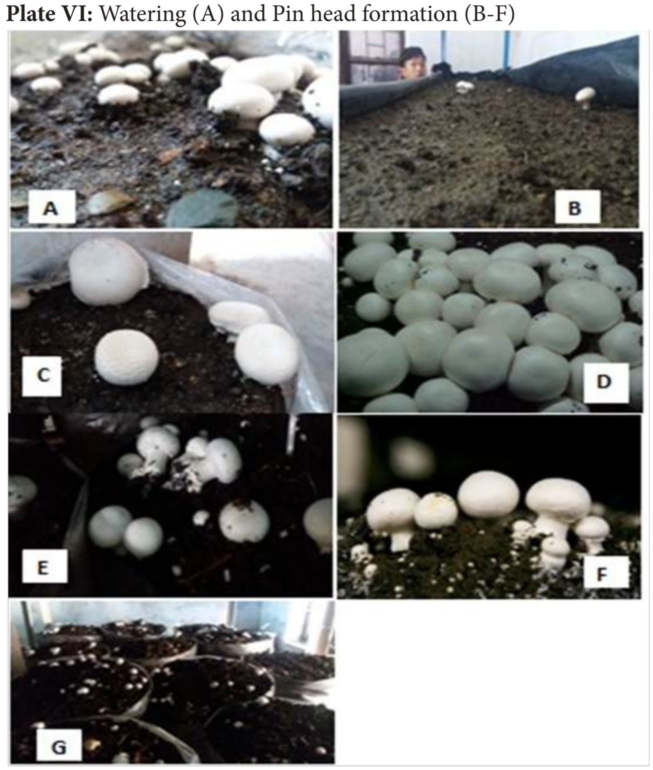

Plate VII: Fruiting Bodies formation- In Shelves (A and B), in Bags (C-G)

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SUSTAINABLE TREKKING PRACTICES FOR REDUCING PLASTIC WASTE IN FRAGILE HIMALAYAN ECOSYSTEMS

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ABSTRACT

The Indian Himalayan Region (IHR), recognized as the "Third Pole" and the "Water Tower of Asia," attracts millions of tourists each year for its scenic landscapes, rich biodiversity, and cultural heritage, but rapid tourism growth has intensified plastic pollution, posing serious ecological risks. Plastic bottles, food wrappers, and synthetic trekking materials form the bulk of solid waste, with trekking zones generating 200–288 g of waste per person daily, over 90% of which consists of plastics and glass. Inadequate disposal methods, including open dumping and burning, pollute rivers, soils, and glaciers, while the breakdown of plastics into microplastics threatens biodiversity, freshwater resources, cultural landscapes, and community livelihoods. Promoting eco-friendly tourism is therefore crucial, encompassing community-based waste management, decentralized composting and recycling, installation of solar-powered refill points, adoption of reusable products, sustainable infrastructure, and conservation of water, energy, and habitats. Strong policy actions such as plastic bans, eco-certification, fines, and waste buy-back systems, supported by visitor education, can encourage responsible practices and strengthen circular economy approaches. Evidence from Himalayan case studies shows that awareness and local participation effectively reduce waste, though financial and infrastructural barriers remain. This study underscores the need for integrated solutionscombining policy, innovation in biodegradable alternatives, microplastic research, and community involvementto shift tourism from an ecological burden to a tool for conservation, enabling the Himalayas to progress toward zero-waste, plastic-free trekking trails that safeguard fragile ecosystems, uphold cultural values, and sustain local economies.

Key words: Indian Himalayan Region, Plastic Pollution, Sustainable Tourism, Community Participation.

INTRODUCTION

The Himalayas, often known as the "Third Pole" and the "Water Tower of Asia," are one of the world's most popular tourist destinations with magnificent natural beauty. Because of its natural beauty, abundant biodiversity, and unique cultural, this mountain range attracts millions of hikers and tourists each year (Apollo *et al.,* 2022). Among its many regions, the Sikkim Himalaya stands out with its sacred lakes, monasteries, and distinctive ethnic cultures, making it a major tourist attraction. While tourism has boosted local economies and livelihoods, the rapid growth of trekking and recreational activities has begun exerting pressure on fragile ecosystems. Therefore, sustainable tourism strategies are vital to balance biodiversity conservation with community welfare (Rai *et al.,* 1997). In addition to tourism pressures, the Indian Himalayan Region faces a mounting challenge of solid waste management, largely driven by increasing tourist inflows. Limited infrastructure, difficult terrain, and harsh climatic conditions make proper collection, segregation, and disposal of waste extremely difficult. Inefficient practices like open dumping and burning not only pollute streams and soils but also accelerate glacier melt, underscoring the urgent need for sustainable waste solutions (Thakur *et al.,* 2021).Plastic pollution is the primary problem that causes these waste management difficult and has become a global environmental emergency. With recycling rates alarmingly low and leakage into both terrestrial and aquatic ecosystems increasing, plastics are now a visible and invisible threat to Himalayan landscapes. From littered trekking trails to microplastics contaminating glacial streams, their impact extends to biodiversity, human health, and downstream water security. Addressing this requires integrating circular economy principles, strong policies, and active community participation to minimize dependence on single-use plastics (Kumar *et al.,* 2021).With its towering peaks, majestic landscapes, and rich cultural heritage, the Indian Himalayan Region (IHR) continues to attract millions of visitors seeking adventure, spirituality, and cultural experiences. While tourism provides vital income and employment, unregulated mass-tourism has begun straining fragile ecosystems and traditional heritage. Issues such as poorly planned infrastructure, inadequate solid waste management, and biodiversity loss highlight the urgent need for sustainable alternatives. Embedding sustainability principles into tourism policies and practices is therefore essential to balance economic growth with ecological preservation (Kotru *et al.,* 2018).Microplastics have been increasingly detected in Himalayan rivers, glaciers, forests, and other ecosystems, often transported long distances via air and water. Tourism-generated plastic waste contributes significantly, with fragmentation of larger plastics leading to persistent microplastic accumulation in pristine landscapes. Effective management requires integrated waste strategies, regulatory interventions, and targeted research to address knowledge gaps in freshwater ecosystems (Bhattacharya *et al.,* 2023). Tourism may be transformed from a pollutant to a conservation force by redesigning the visitor experience around concepts of sustainability, trash reduction, and community engagement. In addition to outlining the fundamentals of environmentally responsible trekking and providing case studies of effective interventions, this study will examine the current extent of plastic pollution from tourism and provide a number of practical suggestions for all levels of stakeholders.

PLASTIC POLLUTION IN MOUNTAIN TOURISM AND THEIR IMPACTS

Every year, millions of tourists and hikers are attracted to the world's mountain regions, especially the Himalayas, by their beautiful scenery. Despite being a crucial economic lifeline, this migration has led to widespread plastic litter, which is an environmental problem. Single-use water bottles, food packaging, and containers for personal hygiene products account for the majority of plastic trash in mountainous areas. The plastic load is further increased by trekking equipment consisting of synthetic polymers, such as ropes and tarps. These plastics are persistent in the environment, contaminating soils, rivers, and forests as they break down into microplastics (Fig .1).In the Indian Himalayan Region, solid waste generation in sensitive tourist areas is 288 g per visitor per day, close to the national average of 350 g per capita per day. Along the 19-km trek to Valley of Flowers and Hem Kund Sahib, nearly 29 metric tonnes of waste is produced during just a 4-month tourist season. Non-biodegradable waste (glass bottles, plastics, metals) accounts for 96.3% by weight, with glass bottles (68%) and plastics (26%) dominating. A coordinated system to transport this waste from trekking routes to road heads like Govind Ghat for recycling, along with public participation, is essential for sustainable management (Kuniyal *et al.,* 2003). In similar Himalayan trekking and expedition areas such as Valley of Flowers (1830–4330 m) and Pindari Valley (2300–5500 m), visitor inflows range from 25,000 to over 116,000 annually. Per capita daily waste generation is 200 g in expedition areas and 288 g in trekking zones, with non-biodegradables dominating. Sustainable management calls for rejection, reuse, recycling, and biocomposting as urgent interventions to turn waste into resources (Kuniyal *et al.,* 2005). In Rakchham village, Himachal Pradesh, waste audits showed recyclables dominated, with plastics (40.8%), followed by glass (36.7%), paper/cardboard (18.4%), and metal (4.1%). A fee-based system run by the village council financed waste operations, while tourism influxes caused seasonal spikes in waste generation. Healing Himalayas conducted 15+ awareness workshops, strengthening community participation and behavioural change. Key challenges remain in financial resources, infrastructure, and cold-climate wet waste treatment, highlighting the need for context-specific solutions (Roy *et al.,* 2024).Plastic contamination in the Himalaya creates serious environmental, socioeconomic, and cultural concerns. Non-biodegradable garbage, such as plastics and glass, has a negative impact on fragile alpine ecosystems. Plastics left on hiking routes and in riparian zones degrade into microplastics, contaminating soils, rivers, and glacier streams. Plastic ingestion by cattle and wildlife disturbs food chains, while leachates and physical debris degrade aquatic environments, posing a threat to biodiversity. Culturally and spiritually significant locations, such as sacred lakes, pilgrimage pathways, and meadows, lose their aesthetic and spiritual significance when rubbish accumulates, reducing the visiting experience and undermining cultural identity. Socioeconomically, communities that rely on agriculture, tourism, and clean water resources face increasing risks. Plastic waste degrades soil fertility, reduces water availability, and raises waste disposal costs, while undesirable landscapes limit tourist satisfaction and revenue for local economies. Seasonal tourism influxes worsen the problem, overloading existing waste disposal facilities. Furthermore, transporting recyclables from outlying settlements to roadheads or

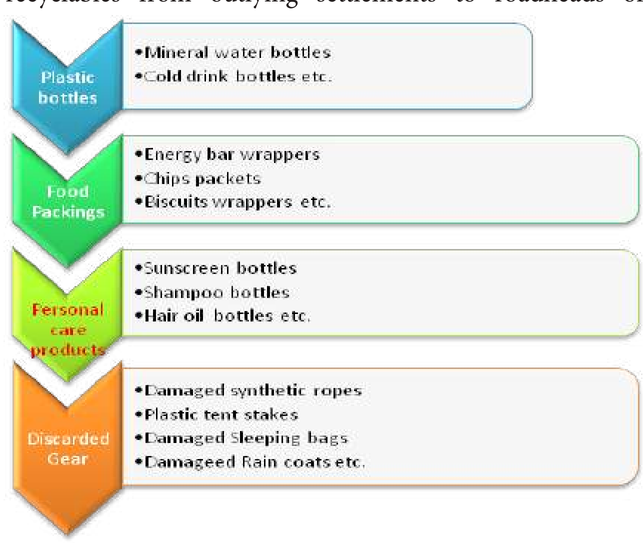

Fig. 1. Types of Plastic Waste from Trekking and Tourism Activities.

recycling centres incurs financial costs. If left unchecked, plastic pollution threatens the long-term viability of tourism and livelihoods in the Himalaya. Addressing these problems necessitates immediate action through policy, community-based efforts, and environmentally conscious visitor behaviour.

Plastic pollution affects Himalayan ecosystems at multiple levels—ecological, socio-economic, cultural, and climatic. These impacts are summarized in Table 1 to provide a clearer understanding of their extent and consequences.

Table 1: Environmental and Socio-Cultural Impacts of Plastic Pollution in the Indian Himalayan Region

Impact Area	Consequences
Climate Impacts	GHG emissions, glacier melt acceleration (Gul *et al.,* 2023)
Freshwater Ecosystems	Threatens drinking water sources (Bhattacharya *et al.,* 2023a)
Agriculture & Livestock	Reduced soil fertility, livestock health issues
Tourism Aesthetics	Decline in visitor satisfaction (Bhattacharya *et al.,* 2023b)
Cultural Heritage	Loss of spiritual value

ECO FRIENDLY TOURISM PRACTICES

Eco-friendly tourism, often known as sustainable or responsible tourism, aims to reduce environmental impact while increasing socioeconomic advantages for local people. Researchers in the Indian Himalayan Region (IHR), whose fragile ecosystems are especially vulnerable to anthropogenic influences, have repeatedly emphasized the importance of implementing eco-friendly practices. Eco-friendly practices in Himalayan homestays involve community-driven waste management, where locals collect, segregate, and process both biodegradable and non-biodegradable waste. Decentralized facilities like composting units and recycling stations minimize environmental impacts while promoting income and skill development. Combined with visitor education and sustainable tourism guidelines, these measures help preserve fragile Himalayan ecosystems and support responsible tourism (Chandel *et al.,* 2024). Trekking areas implement waste collection and transport systems to move refuse from trails to recycling and composting facilities. Non-biodegradable materials are recycled, while organic waste is composted to recover resources. Community involvement and visitor awareness foster responsible behaviour and support long-term ecosystem conservation (Kuniyal *et al.,* 2003). Eco-friendly tourism in the Himalayas can be promoted by minimizing single-use plastics, developing eco-friendly infrastructure such as solar-powered campsites and energy-efficient facilities, and encouraging sustainable mobility like walking, cycling, or limiting vehicle access. Water and energy conservation through rainwater harvesting and renewable energy reduces environmental pressure. Protecting habitats and biodiversity with proper trail maintenance and litter prevention, along with policy and regulatory support like bans and eco-certifications, ensures long-term ecosystem sustainability (Chandel *et al.,* 2024) (Fig. 2).

Fig. 2. Approaches to Sustainable and Responsible Tourism

RECOMMENDATIONS

To ensure sustainable tourism in the Indian Himalayas, a multi-pronged approach is essential. Eco-certification schemes for trekking operators and homestays should be established, emphasizing waste management, use of reusables, staff training, and community engagement, with certified businesses promoted through official tourism channels. Infrastructure development is critical, including solar-powered water refill stations along trails, enabling trekkers to avoid single-use plastic bottles. Strict enforcement of plastic bans and fines for littering should be applied consistently, with collected funds reinvested in local waste management and conservation initiatives. Community-led waste enterprises can manage collection, segregation, and low-tech recycling, generating green employment and promoting stewardship. Waste buy-back schemes in gateway towns can incentivize proper disposal by providing monetary rewards for returned plastics. Public awareness must be integrated into national and state campaigns, including pre-trek briefings, signage, and guide-led education, to encourage responsible behaviour. Finally, research and innovation should focus on biodegradable alternatives, microplastic monitoring, and sustainable tourism practices. Collectively, these strategies support a zero-waste trail concept, reduce environmental impacts, empower local communities, and protect fragile Himalayan ecosystems while maintaining the region's tourism appeal.

CONCLUSION

Tourism in the Indian Himalayas provides critical economic benefits but also places immense pressure on fragile ecosystems, particularly through plastic pollution. Single-use plastics, non-biodegradable waste, and synthetic trekking materials contaminate soils, rivers, and glaciers, threatening biodiversity, cultural heritage, and community livelihoods. Eco-friendly tourism practices, including community-driven waste management, decentralized recycling and composting, sustainable infrastructure, and visitor education, are essential to mitigate these impacts. Strategies such as minimizing single-use plastics, implementing refill stations, promoting reusable materials, and establishing eco-certification for trekking operators foster responsible tourism while empowering local communities. Policy support, strict enforcement of plastic ban, waste buy-back schemes, and integration of public awareness campaigns further strengthen these efforts. Additionally, research into biodegradable alternatives and microplastic monitoring provides critical insights for long-term sustainability. By combining community engagement, policy intervention, and environmentally conscious visitor behaviour, the Himalayas can transition toward a zero-waste, plastic-free tourism model that preserves ecological integrity and supports resilient local economies.

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CLIMATE CHANGE ADAPTATION AND CULTURAL ECOLOGY: EXPLORING THE ROLE OF HADIMBA SACRED GROVE IN KULLU VALLEY, HIMACHAL PRADESH

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ABSTRACT

Sacred groves are one of the oldest forms of community-based forest conservation. They merge religious beliefs and ecological sustainability into a system of traditional resource management. These groves are recognized as "traditional climate-resilient commodities" because they provide ecological, cultural, and livelihood benefits to local communities and buffer them against environmental and climatic stressors. This study explores the Hadimba Sacred Grove in Manali, Himachal Pradesh, to understand its role in biodiversity conservation, ecosystem services, cultural preservation and climate change mitigation. This study also revealed the provisioning, regulating, supporting, and cultural ecosystem services of the grove. Sacred groves are rich in medicinal flora, carbon-sequestering deodar forests and spiritual beliefs. These groves facilitate hydrological and nutrient cycling, provides habitat for Himalayan flora and fauna, supports pollinators, and upholds the local cultural identity rooted in Hadimba Devi worship. Yet, the grove faces threats from unregulated tourism, climate variability, shifting cultural practices, and infrastructural development. The study highlights how national and international policies such as the Biological Diversity Act (2002), National Biodiversity Action Plan, and Convention on Biological Diversity align with the conservation of sacred groves and provide frameworks for integrating them into climate mitigation and adaptation strategies. It also emphasizes the role of ecotourism and community participation in ensuring the grove's sustainable management.

Key words: Sacred groves; Climate resilience; Ecosystem services; Hadimba Sacred Grove; Biodiversity conservation

INTRODUCTION

Sacred groves are patches of forest traditionally protected by communities because of their association with deities, spirits, or ancestral worship. They are scattered across India and are among the oldest examples of in-situ biodiversity conservation systems (Malhotra *et al.,* 2001). In India, sacred groves are known by several names such as Kavu in Kerala, Devara Kadu in Karnataka, Law Kyntang in Meghalaya, Devrais in Maharashtra, Khejarliin Rajasthan, Dev ban or Devta ka jungle in Himachal Pradesh (Khan *et al.,* 2024). These ecological islands acting as living museums of biodiversity and as cultural commodities that sustain religious, social, and ecological values simultaneously. Recent studies cite them as "climate-resilient commodities" because of their role in buffering local communities from climate variability, providing provisioning and regulating services, and ensuring ecological continuity (Chandran and Gadgil, 1998).Generally, sacred groves are managed by local communities, temple committees or by government bodies like the Forest Department. A good number of sacred groves are found scattered in the Indian Himalayan region. About one lakh sacred groves were reported in India. Out of which, highest number of 5000 sacred groves were found in the state of Himachal Pradesh (Kandari *et al.,* 2014). The Kullu valley is a home to 109 sacred groves documented in HP Biodiversity Report, 2020 that cater over 10,000 plant species, 300 mammal species, and 1000 bird species, with many listed as IUCN endangered species. The Hadimba Sacred Grove in Manali, Kullu district of Himachal Pradesh, is one of the 109 sacred grove that depicts interconnection of ecology, culture, and climate resilience.

CASE STUDY: HADIMBA SACRED GROVE

Hadimba Sacred Grove nestled in the divine town of Manali in north-western Himalayas, holds a rich heritage of biodiversity conservation. Below are some fascinating facts about this grove.

Location: The Hadimba Sacred Grove is located in Dhungri village of Manali in Kullu district of Himachal Pradesh, India. The location of grove shown in Fig.1. It lies at coordinates 32.243°N and 77.189°E, at an altitude of 2,050 meters above sea level. It lies in a temperate Himalayan ecosystem, characterized by snow-bound winters, cool summers, and average annual precipitation of 1,500 mm. It is in the close proximity of the town centre, Manali Mall Road.

Hadimba Devi Temple: The area of sacred grove surrounding the temple of Hadimba Devi temple is shown in Fig.2. Hadimba temple is also known as Dhungri temple. The grove is dedicated to Hadimba Mata, the wife of Bhima (one of the pandavas) and the mother of the mighty warrior Ghatotkacha from the Mahabharata. The Hadimba temple was built in 1553 by Maharaja Bahadur Singh in Pagoda style, represent both religious reverence and ecological sanctity. Architecturally, it is similar to Tripura Sundari temple in Naggar. The pinnacle of the temple rises as high as deodar trees surrounding it in a four-tier pagoda style wood and stone structure (Fig 3 and 4).

Festivals, Traditions and Rituals: For local community, groves serve as the site for religious gatherings, cultural practices, traditional rituals and festivals. Traditional festivals such as Dhungri fair in May celebrated every year to mark the birth anniversary of Hadimba Devi. The event symbolizes the commitment of local communities towards the forests and goddess. It attracts thousands of pilgrims and tourists, providing a cultural economy that is closely linked to the grove's existence. Traditional rituals fullfill the duty to pass down the significance of the grove from generation to generation (Bera, 2023).In times of natural disasters or calamities, local people invoke Hadimba Mata with deep faith, believing that her divine energy protects the land and its people.

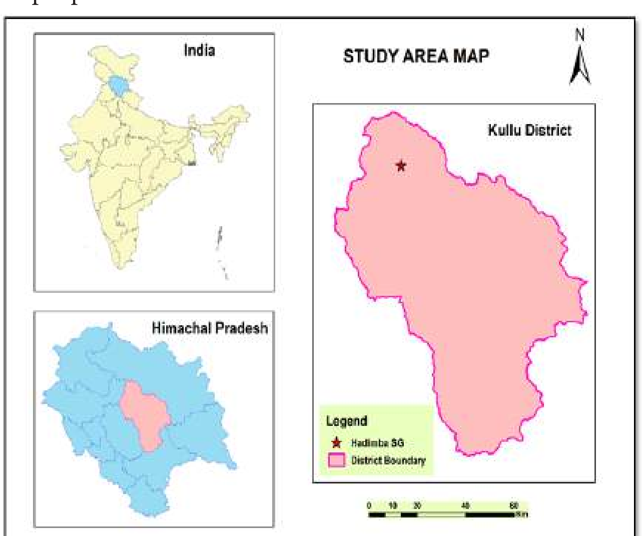

Fig 1: Location of Hadimba sacred grove

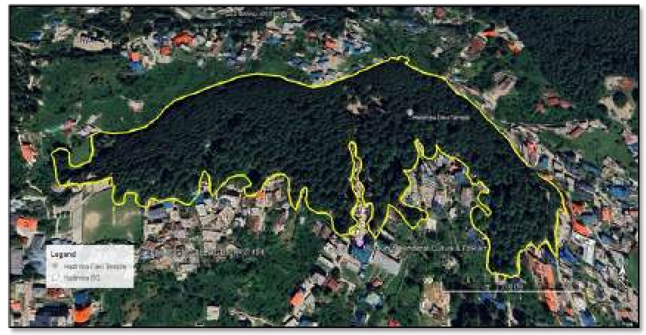

Fig 2: Demarcated Area and location of Hadimba sacred grove

Fig 3: (a&b) Hadimba sacred grove (in the background) with Pagoda style Hadimba Devi Temple and Hadimba Mata Rath

MANAGEMENT OF SACRED GROVE

The grove is managed by Archaeological Survey of India. Activities such as logging, hunting, and extraction of forest resources (trees) are restricted in the grove. Collection of dry wood, litter, NTFP (Non- Timber Forest Produce), fruits and flowers are allowed. The grove has never been subjected to extensive deforestation due to the fear of divine vengeance, that ensured its conservation so far. The local community also plays a significant role in the maintenance of grove since ages. Their role is deeply connected with their religious beliefs, culture and traditions.

ECOSYSTEM SERVICES

Like other groves, Hadimba sacred grove is the multifunctional system provides provisioning, regulating, supporting, and cultural services.The grove is dominated by *Cedrus deodara* (deodara), followed by Quercus (oak), *Pinus roxburghii* (chirpine), and provides medicinal plants such as *Bergenia ciliata* locally known as Pashanbhed or Patharphod. Deodar trees of Hadimba sacred grove have a significant carbon sequestration potential, with study of (Pandey and Awasthi, 2015) indicating an annual net carbon sequestration rate of approximately 3.189 mg C/ha/yr, while the total biomass can increase considerably over a time period 100 years. The potential of carbon sequestration is influenced by factors like tree density and climatic conditions, with soil carbon also increasing over time to contribute to overall carbon stocks. Few species of orchids were also reported from Hadimba Devii.e. *Calanthe tricarinata* (Monkey Orchid), *Epipactis helleborine* (Broad-leaved Helleborine) and *Herminium lanceum* (Lanceleaf Herminum) (Kumari et al., 2016). It also supports species of Himalayan fauna including birds as well as small mammals. It provides pollination services by preserving diverse, undisturbed plant and animal communities, including essential populations of pollinators like bees and birds. In 2025, thirty six bird species mainly includes *Columbia livia* (Rock Pigeon), *Phyconotus leucogenys* (Himalayan Bulbul), *Phylloscopus xanthoschistos* (Gray-hooded Warbler), *Horonisforticeps, Myophonus caeruleus, Acridotheres tristis, Yuhina flavicollis, Eudynamys scolopaceus, Milvus migrans* (Black Kite),*Psilopogon virens* (Great Barbet), *Urocissa flavirostris* (Yellow-billedBlue-Magpie), *Corvus splendens* (House crow), *Corvus macrorhynchos* (Large-billed Crow), *Prinia socialis* (Ashy Prinia), *Passer domesticus* (House sparrow), *Passer cinnamomeus* (Russet Sparrow), *Arborophila torqueola* (Hill Partridge), *Lophura leucomelanos* (Kalij Peasant), *Gyps himalayensis* (Himalayan Griffon) etc. were sighted in the vicinity of temple (EBird India, 2025).

The Hadimba sacred grove plays an important role in the micro-climate regulation in Manali. Transpiration from the sacred groves increases atmospheric humidity and decreases the temperature in the surrounding area (Bhowal, 2021).

TOURISM

Hadimba sacred grove is one of the major tourist spots of the Beas valley. The Hadimba temple is at a distance of about 2.5 km from the Manali city centre. Attractive flora and fauna showcase whisperings of Himalayan birds, blooming orchids and coniferous deodar trees that serve aesthetic values to tourists. It attracts the devotees, nature lovers, pilgrims, architecture lover, educational and cultural tourists. Devotees visit the temple to seek Hadimba Mata blessings for strength, protection, and relief from calamities. Deep religious beliefs, festivals, traditional culture and pristine environment of grove also attract foreign visitors. The other tourist sites in the vicinity of the Hadimba temple are Ghatotkach temple, Museum of Himachal Culture and Folk Art, Hamta Pass and Gadhan Thekchhokling Gompa Monastery.

LOCAL ECONOMY

Tourism generates job opportunities to local people in various sectors, including hospitality, transportation and local handicrafts. Hospitality includes small scale food stalls, cafes, and restaurants that serve traditional Himachali cuisine such as Siddu etc. Among the various other activities, the local people charge rupees vary from Rs. 20-100 per person for capturing photographs with rabbits, for wearing traditional dresses, for riding yak, etc.

THREATS TO HADIMBA SACRED GROVE

Sacred groves are one of the most valuable traditional practices of nature conservation which have been completely immune from human intervention due to religious beliefs (Gadgil and Vartak, 1974). But the growing demand for land and natural resources due to urbanization, tourism population growth have threatened the preservation of the sacred groves.

The paradigm shifts in cultural practices, changing demographics of Manali and modernization has threatened the future of this sacred grove. The educated population is migrating to cities, for better quality of lifestyle besides urbanization and tourism boost has led to need of roads, housing and infrastructure has resulted into encroachment of the sacred groves area (Saha, 2024). Rapid tourism growth in Manali has led to increased air and noise pollution that deteriorates the quality of local environment. Climate patterns are being altered due to rising vehicular emissions and deforestation linked with tourism activities (Kuniyal *et al.,* 2003). Climate factors, such as temperature and rainfall play a role in influencing the carbon sequestration potential of deodar forests (Pandey *et al.,* 2015). But the risk of changing climate patterns has threatened the longevity of deodar trees and other species of Hadimba grove which can be influenced by climate alterations.

NATIONAL POLICIES AND SACRED GROVE CONSERVATION

Sacred groves regarded as the epicentre of ecological conservation research and policy formulation regarding conservation and management of forests at State and at the National Level (Ray and Ramachandra 2010). The various researches were made at national and state level in an attempt to document, preserve and conserve the unique biodiversity of sacred groves. (Dudley *et al.,* 2009) highlighted "bringing a sacred natural site into a national protected-area system can increase protection for the site, but may compromise some of the spiritual values or even its conservation values".

Sacred groves are legally protected under 'community reserves' in the Wildlife (Protection) Amendment act, 2002. It revolves around the direct participation of local communities in preserving natural resources and wildlife. The Forests Rights Act (2006) gave rights to local and tribal communities to act as custodians of these groves. Under AMASR Act, 1958 Hadimba temple brought under the management of ASI (Archaeological Survey of India). It is responsible for the management of Hadimba sacred grove as it was declared a protected monument under ASI.

'Travel for LiFE' (TFL) program under Mission LiFE (Lifestyle for Environment) and Travel for Life Pledge for visitors and residents launched by Ministry of Tourism which aims to minimize the negative effects of tourism and develop a culture of sustainability in tourism sector by adopting sustainable and eco-friendly practices, guided by principles like environmental conservation, biodiversity preservation, cultural awareness and community inclusion. Awareness programs, workshops, capacity building programs, webinars etc. must be organized to promote Sustainable and Ecotourism in Manali that ultimately leads to the goal of preserving the sanctity of Hadimba Sacred Grove. The management of Sacred Grove has been aligned with three major landmark national agreements that had significant bearing on biodiversity conservation and climate change. These are Environment (Protection) Act, 1986, Biological Diversity Act, 2002, National Mission for Green India, 2014, a part of National Action Plan on climate Change.

The grove aligns with the OCEM (Other Effective Area-Based Conservation Measures) approach under the Convention on Biological Diversity, 1992. Biological Diversity Act, 2002 undertake the implementation of CBD's provisions in India. It ensures long-term conservation outcomes that preserves its biodiversity and ecosystem functions. Sacred groves of Himalayas contribute to protect their unique flora and fauna. They act as natural carbon sinks that further contribute to achieve the India's net-zero target by 2070, alongside with other forests. Sacred groves are least governed by legal frameworks and their conservation is led by norms and taboos such as fear of divine retribution. Therefore, for the conservation of sacred groves, stringent legislation with punishment is needed (Kandari *et al.,* 2014).

IMPACTS OF CLIMATE CHANGE AND ADAPTATION PRACTICES

Climate change adaptation means the actions that mitigate the vulnerability to the current or anticipated consequences of climate change such as weather extremes and hazards (cloudbursts, floods, earthquakes, landslides, heat waves etc.), sea-level rise, food and water insecurity, biodiversity loss, etc.

Lindsey *et al.,* 2020 study shows that 2024 was recorded as the warmest year since 1850. The global average surface temperature increased by 1.46 degrees Celsius since the pre industrial Era (1850-1900) indicating a significant increase in heat energy circulating through throughout the earth's system including oceans, frozen landscapes and atmosphere. Climate change impacts are increasing with every degree of warming, making adaptation harder and more expensive. Therefore, climate change adaptation is particularly urgent for developing countries, who are already vulnerable due to their geographical and climatic conditions. The topography of Himachal Pradesh is characterized by steep slopes and mountainous terrain, making it highly susceptible to landslides and other hazards like flash floods and avalanches, exacerbated by active plate tectonics, heavy rainfall, and human activities such as deforestation and road construction (Jallayu *et al.,* 2025). The state's ecologically sensitive Himalayan ecosystem is vulnerable to climatic changes, which are increasing threats to its food security, livelihoods, and biodiversity. Climate change projections indicate the adverse impacts on water resources which is necessary for sustainable development.

A study by the Central Ground Water Board indicates that more than 50% of the springs in the Indian Himalayas are dying up, affecting water availability for millions. During peak tourism months, water demand of Manali is higher than usual (Anke Kirch, 2002).According to HP Forest report, 2021 there was a decline of 902 square kilometres in forest cover as compared to the 2019. Overall, there was loss of 1,072 square kilometers of forest cover in Indian Himalayan region. The National Disaster Management Authority's post disaster assessment of the 2023 floods in Kullu, Himachal Pradesh attributed the disaster to widespread illegal logging and construction on river beds, flood plains primarily to boost the tourism of the region. NDMA recommended a series of regulations that would create a buffer zone and restrict checked tourism in Glacial Lake Outburst Floods prone areas and nearby regions in order to reduce the scale of pollution and change in climatic conditions in these areas.

CLIMATE-RESILIENT TECHNOLOGIES

Promising climate-resilient technologies include rejuvenation of traditional water systems (Baudi, Katri, Kuhul) and enhanced groundwater recharge to ensure 24/7 availability of clean water in the peak tourism period of the Kullu valley. Under the NICRA (National Innovations in Climate Resilient Agriculture) program low-cost ponds (Jalkunds of 6-60 Kiloliters capacity) and rainwater harvesting structures were constructed in Kullu, Chamba region that improved the water availability for agriculture and drinking purposes (Singh *et al.,* 2022).

PROMOTION OF TRADITIONAL ARCHITECTURE

Buildings in the Kullu region traditionally constructed in Kath-Kuni style, which have a lower embodied energy and a smaller carbon footprint compared to modern concrete structures (Panwar *et al.,* 2022). This style use passive elements such as sunspaces and verandas to manage indoor temperatures naturally, decreasing reliance on energy-intensive heating and cooling systems. Blending these techniques with contemporary building practices and technology can create structures that are both environment friendly and meet modern safety standards.

ESTABLISHMENT OF ARBORETUM

An arboretum in Shimla and Kullu districts managed by HFRI (Western Himalayan Temperate Arboretum, Shimla) and GB Pant National Institute of Himalayan Environment, Mohal, Kullu helps in mitigate climate change by conserving biodiversity, acting as living seed bank for native tree species, and providing research and educational opportunities to develop climate-resilient strategies for the vulnerable Himalayan ecosystem. Such arboretum in Manali should be established and implement by the HP State CAMPA (Compensatory Afforestation Fund Management and Planning Authority) in collaboration with local communities. The tree species include deodara, oak, chir pine, etc. These native species capable of thriving in snow and heavy rainfall condition. (Ahmad *et al.,* 2018) study depicts that the deodar sacred groves had the stronger potential to sequester and store atmospheric carbon in the recent climate change environment. By preserving the native species and promoting ecological understanding of Sacred grove through community awareness programs can contribute to the overall health of ecosystems, which is vital for the regions's adaptation and resilience against climate change.

CONCLUSION

In the Himalayan region, sacred groves hold an important status due to their ecological sensitivity, cultural richness and dependence of local livelihoods on forest ecosystems. The sacred groves are valuable for their biological diversity, but due to changing mindsets, tourism influx and development activities groves were depleting. This study intended to explore the role of Hadimba sacred grove in conservation and management of different ecosystem services.

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DISTRIBUTION AND DEPOSITION OF MICROPLASTICS IN THE INDIAN HIMALAYAN ATMOSPHERE

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ABSTRACT

Microplastics (MPs), which are plastic particles smaller than 5 mm, have become commonplace pollutants in freshwater, marine, terrestrial, and atmospheric environments. Recent studies have confirmed that atmospheric transport and deposition play a significant role in the delivery of microplastics to high-altitude and remote areas, such as the Indian Himalaya. This article summarizes what is currently known about the prevalence, traits, sources, and modes of transport of atmospheric microplastics in the Indian Himalayan region, as well as their possible effects on the environment and human health. This study reviews modeling studies of long-distance airborne transport, field observations (including recent deposition measurements near the foothills of the Himalayas and detections in high-altitude lakes/glaciers), and the role of local meteorology and monsoon in mediating deposition. Standardized sampling and analysis procedures, limited spatial-temporal coverage (especially at high elevations), and a lack of toxicological data pertinent to Himalayan communities and ecosystems are among the clear knowledge gaps identified in the review. It also recommends focused research and policy actions to monitor, mitigate, and manage atmospheric microplastics in the region.

Key words: Microplastics; Atmosphere; Himalayas; Ecosystems; Mitigation;

INTRODUCTION

The worldwide manufacture and utilization of synthetic polymers have resulted in an enduring accumulation of plastic waste. Over time, macroplastics break down into microplastics (MPs), which are usually defined as particles that are less than 5 mm in size, and nanoplastics (Yadav *et al.,* 2024). At first, people were mostly interested in aquatic environments, but more and more evidence shows that microplastics are airborne and can travel long distances, landing on land, ice, and water far from where they came from. The Himalayas and other mountainous areas are no longer clean places to live. Measurements of the air and sedimentary records show microplastics in snow, glacier ice, high-altitude lakes, and soil. This is bad for both the fragile mountain ecosystems and the people who live there. Recent targeted studies in and around the Indian Himalaya yield the inaugural regional estimates of atmospheric deposition and particle characterization (Talukdar *et al.,* 2023). Models suggest that atmospheric transport from urban and coastal source areas across South Asia can effectively convey microplastics to elevated altitudes (Zhang *et al.,* 2020). This paper collects and puts together all the research that has been done on atmospheric microplastics in the Indian Himalayan region. It focuses on: documented occurrence and particle characteristics; emission sources and transport mechanisms (local and long-range); meteorological controls, including the monsoon; ecological and human-health implications for Himalayan systems; and research and policy priorities.

DEFINITIONS AND ANALYTICAL CONSIDERATIONS

"Microplastics" is a term that is commonly used to refer to plastic particles that are less than 5 mm in size, such as fibers, fragments, films, foams, and beads. Studies differ in size thresholds (typically ranging from 1 µm to several millimeters), sampling techniques (including active air sampling using pumps and filters, as well as passive deposition collectors), extraction and visual identification methods (such as microscopy), and polymer verification techniques (like FTIR, Raman spectroscopy, and Py-GCMS). Due to the significant impact of analytical methodologies on reported concentrations and size distributions, cross-study comparisons should be conducted with caution. To get a clear picture of the region, it needs standardized protocols for airborne MP sampling, contamination control (like procedural blanks and laboratory clean air), and polymer identification.

DOCUMENTED INCIDENCES IN THE INDIAN HIMALAYA AND ADJACENT FOOTHILLS

Fieldwork in the Indian Himalayas and its foothills has shown that microplastics are present in the air and settle on surfaces and ecosystems. A recent field study in an urban area near the foothills of the Indian Himalayas looked at how microplastics fell from the sky. It measured how much microplastics fell, described the shapes and types of polymers, and talked about where they probably came from and how they got to the area. The study found that deposition rates were higher and that fiber-dominant particle accumulations were present. This suggests that textiles and urban waste are important sources. More research in the greater Himalayan region has found microplastics in high-altitude lakes, glacier meltwater, soils, and river deposits. This is consistent with an atmospheric source sending fibers and small pieces into places that are otherwise hard to reach. Reviews that put these observations together show that fibers are often the most common shape in atmospheric fallout and in high-altitude lake sediments in the Himalaya (Dong *et al.,* 2021).

SOURCES OF ATMOSPHERIC MICROPLASTICS AFFECTING THE HIMALAYA

The Indian Himalayan region is increasingly affected by atmospheric microplastics (MPs), which originate from a variety of local, regional, and long-range sources. Understanding these sources is crucial for addressing the growing environmental concern posed by microplastics in this ecologically sensitive area (Wang *et al.,* 2023). Local urban and domestic sources are significant contributors to atmospheric microplastics. One of the primary sources is textile fibers, which are released indoors through activities such as clothing abrasion, laundry, and the operation of heating, ventilation, and air conditioning (HVAC) systems. Additionally, waste management sites and landfills significantly contribute to airborne microplastics (Feng *et al.,* 2020).Poorly managed waste sites near urban areas can produce microplastics carried by the wind.

TRANSPORT PATHWAYS AND METEOROLOGICAL CONTROLS

Microplastics are moved to and around the Himalayan region through both dry and wet deposition. This is controlled by the size, density, shape, weather, topography, and boundary-layer dynamics of the particles:

Uplift and long-range transport: Convection, turbulence, and frontal systems can lift small fibers and pieces into the free troposphere, where they can be moved over long distances. Particles that are tens to hundreds of micrometers in size can stay suspended long enough to move from flat, populated areas to the foothills of mountains and higher elevations (Padha *et al.,* 2022). Modeling studies for Asia, including the Indian subcontinent, indicate that such uplift and subsequent transport are feasible and can explain the observed MPs in remote regions.

Orographic trapping and deposition: When air masses rise up mountain slopes, they cool down and lose water. Orographic uplift increases the deposition of aerosols and particles on mountain surfaces, with the most deposition happening on windward slopes and in valley systems (Evangeliou *et al.,* 2020).

The Indian summer monsoon (about June to September): changes the patterns of wind and rain, which could lead to more wet deposition (washout) of airborne MPs during heavy rains but also allow transport in low-level jets before storms. Changes in circulation between the monsoon and winter seasons cause different patterns of transport and deposition throughout the year.

In general, these processes mean that the Himalayas can get a mix of new particles that have just been released into the air and old particles that have been moved from faraway places. Fibers are often the most common size and shape that atmospheric pathways bring.

PARTICLE CHARACTERISTICS REPORTED IN THE REGION

There are some common patterns that come up in many Himalayan studies:

Shape: In many studies, especially those done in remote and high-altitude areas, fibers make up most of the airborne and deposited MPs. Fragments are also present, but they are usually more common near larger point sources. Textile wear and home sources make a lot of fibers, and they are easy to lift because they have low aerodynamic settling speeds.

Types of polymers: Some common polymers are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyamide (nylon), and polystyrene (PS). PET and polyester (a type of PET) are common in places where textile fibers are common. PE and PP are common in places where packaging is broken. In Himalayan studies, FTIR and Raman spectroscopy have been used to confirm polymer identification. However, some studies still use visually classified particles, which can overestimate MPs without polymer confirmation.

Size distribution: MPs in the air and on surfaces are usually smaller (from a few hundred micrometers to a few micrometers), but different studies use different size cutoffs.

ENVIRONMENTAL AND POTENTIAL HUMAN-HEALTH IMPLICATIONS

Ecological consequences for Himalayan systems

The Himalayas have unique and fragile ecosystems, such as alpine meadows, streams fed by glaciers, and lakes at high altitudes (Allen *et al.,* 2019). These ecosystems provide water, biodiversity, and ecosystem services. Microplastic accumulation in soils, snowpacks, and aquatic environments can yield various ecological consequences:

Physical effects: When aquatic and terrestrial organisms (like filter feeders, invertebrates, fish, and birds) eat plastic, it can make it harder for them to eat, cause internal abrasion, or even block their passage in severe cases. Microplastic pollution that can get into food webs is already present in lakes and streams at high altitudes.

Chemical effects: Microplastics can absorb and move pollutants (like heavy metals and persistent organic pollutants) and may leach additives (like plasticizers and stabilizers) that have harmful effects on living things (Brahney *et al.,* 2020).

Ecosystem-level effects: sustained deposition may lead to alterations in microbial communities on particle surfaces (the "plastisphere"), modifications in sediment physical properties, and shifts in nutrient cycling; however, empirical data from Indian Himalayan systems are currently scarce.

Human-health concerns

Himalayan communities, encompassing indigenous peoples, mountain laborers, and downstream populations reliant on glacial and riverine water, may be susceptible to microplastic exposure through the inhalation of airborne particles, the consumption of contaminated water or food (such as fish, freshwater mussels, and alpine produce), and occupational exposures. Microfibers in the air can settle in human lungs (Dris *et al.,* 2016). Studies from other places have shown that breathing in microfibers can cause lung inflammation and, in some groups, the presence of plastic particles in lung tissue. Nonetheless, direct causal relationships between environmentally realistic exposures in the Himalayas and particular health outcomes remain inadequately defined by existing data. Consequently, health risk assessments for the region must integrate exposure monitoring with toxicological research focused on the specific sizes, shapes, and polymer chemistries present locally.

Case studies and notable regional findings

Atmospheric deposition near Himalayan foothills

In 2024, a study was conducted on an urban conglomerate located near the Indian Himalayan foothills. The study measured atmospheric deposition fluxes, characterized particle morphologies and polymer types, and proposed transport pathways and potential sources. Compared to other regional datasets, the study reported elevated deposition fluxes and emphasized the dominance of fiber shapes, indicating that textile and urban refuse sources are significant contributors to airborne MPs in the foothill region (Zhang *et al.,* 2020). This is one of the first targeted investigations to provide quantitative deposition data in the Indian Himalayan context, thereby bridging the gap between field observations and modelling predictions.

High-altitude lakes and glacier environments

Recent investigations across the Himalaya (including glacier meltwater and high-mountain lakes) repeatedly detect microplastics, often dominated by fibers, indicating atmospheric deposition and meltwater inputs as important pathways (Huang *et al.,* 2021). These findings reinforce that even remote alpine water bodies are not immune to anthropogenic plastic pollution and that MPs have accumulated in sediments and biota in some high-altitude settings.

Knowledge gaps and methodological challenges

Despite the expansion of the literature, there are still numerous critical gaps: Spatial and temporal coverage: The majority of studies are focused on the vicinity of population centers, foothills, and a few alpine locations. Throughout the entire Himalayan region, there is inadequate systematic monitoring of seasonal cycles and altitudinal gradients. Standardization: The inability to conduct cross-study comparisons and meta-analyses is exacerbated by the heterogeneity in sampling (active vs passive), size cutoffs, contamination controls, and polymer confirmation. Source attribution: although fibers indicate textiles and urban sources, quantitative source apportionment that integrates isotopic tracers, chemical markers, and atmospheric back-trajectory modeling is still limited for the region. Exposure and toxicity: The ecological and human health effects that are unique to Himalayan exposure scenarios are still inadequately understood, particularly chronic inhalation exposures to microfibers for indoor/outdoor workers and gastrointestinal exposures through locally produced food and water. The role of snowmelt, glacial retreat, and land-use change in remobilizing legacy deposited MPs requires clarification in the context of resuspension dynamics. To address these voids, it will be necessary to conduct coordinated, multidisciplinary research across the fields of ecology, atmospheric science, toxicology, and social science (Feng *et al.,* 2021).

Research priorities and methodological recommendations

Standardize protocols: use the same sampling methods (like using both active samplers for particle size distributions and passive fallout collectors for deposition flux), strict contamination controls, and polymer confirmation (FTIR/Raman) with size distributions and recovery efficiencies reported. Set up monitoring networks: set up a network of sampling sites that are spread out across altitudinal transects (from lowlands to foothills to mid-Himalaya to high-altitude sites) and across seasons to see how the monsoon and non-monsoon seasons affect each other. Integrate observations with modeling: correlate measurements with atmospheric transport and deposition modeling (incorporating source-receptor analysis and trajectory back-tracking) to assess contributions from local and long-range sources (Wang *et al.,* 2022).

Targeted toxicology: carry out inhalation and ingestion exposure studies utilizing environmentally pertinent particle dimensions, polymers, and co-contaminant concentrations identified in Himalayan specimens. Community science and capacity building: get local people and regional institutions (like universities and mountain research centers) involved in systematic sampling and raising awareness. This will help build local capacity for ongoing monitoring.

POLICY, MANAGEMENT, AND MITIGATION

To cut down on microplastics in the air in the India Himalayan region, it needs to make changes on many levels:
Source reduction: put more emphasis on cutting down on the release of textile fibers (for example, by encouraging the use of washing machine filters and low-shedding textiles), improve the management of plastic waste in plain and peri-urban areas, and stop open burning and unregulated landfill operations.
Waste management improvements: put efforts into secure landfills, segregation, recycling infrastructure, and formalized waste-collection systems in cities whose emissions can carry MPs into the mountains.
Regulatory actions: make and enforce rules that limit single-use plastics, support producer responsibility schemes, and encourage alternatives to harmful polymer uses in agriculture and packaging.
Public health and education: Teach people about indoor sources of pollution, like fibers from clothes and dust in the home. Encourage ventilation and filtration solutions for indoor spaces, and include microplastic exposure in public health monitoring.
Transboundary cooperation: because air pollution can travel across borders, South Asian countries need to work together to keep an eye on it, control its sources, and come up with shared ways to reduce it.

CONCLUSIONS

The Indian Himalayan region is getting measurable amounts of atmospheric microplastics, with fibers often making up the majority of particle groups. Field measurements close to the Himalayan foothills and detections in high-altitude lakes and glacier melt streams validate that atmospheric pathways transport plastics into mountainous ecosystems. Modeling work backs up the idea that things can be moved over long distances from crowded plains and coastal areas to the highlands. The effects on delicate alpine ecosystems and on human communities that rely on mountain water and food resources could be very bad, but we don't know exactly how bad they will be. To understand and stop the movement of microplastics to the Himalayas, we need a coordinated program of standardized monitoring, source reduction, better waste management, and targeted toxicological studies. To protect both mountain ecosystems and people's health, policymakers should include microplastic issues in broader frameworks for waste, air quality, and public health.

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ASSESSING THE VARIABILITY OF GLACIER MELTWATER DISCHARGE IN THE CENTRAL AND WESTERN HIMALAYAN REGIONS, INDIA

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ABSTRACT

The Himalayan region, often referred to as the "Third Pole," is a critical reservoir of freshwater, with glaciers acting as natural water towers that sustain river systems across South Asia. This study synthesizes discharge records from 6 glaciers across Central and Western Himalaya to evaluate spatial and temporal variability. In Ladakh, glaciers such as Stok, Phuche, and Parkachik exhibit modest to moderate discharges, reflecting cold-arid conditions, small catchment sizes, and limited precipitation, with Parkachik standing out due to its larger ice volume. Chhota Shigri in Himachal Pradesh demonstrates intermediate to high meltwater outputs, strongly influenced by both westerly winter snowfall and summer monsoon rainfall, resulting in pronounced seasonal and interannual variability. In Uttarakhand, large glaciers like Gangotri contribute substantial melt water to the Bhagirathi River, while medium-sized glaciers such as Dokriani illustrate clear seasonal discharge patterns. The study reveals a distinct west-to-east gradient in glacier discharge, controlled by glacier size, regional climate, and monsoon influence. These findings highlight the critical role of Himalayan glaciers in maintaining downstream water resources and highlight their vulnerability to climate change. Anticipated shifts in precipitation and temperature regimes are likely to alter the timing and magnitude of melt water availability, posing challenges for water security, agriculture, and hydropower management across the region. This synthesis provides a baseline for future hydrological assessments and supports adaptive water resource planning in the Central Western Himalaya.

Key words: glacier melt water discharge, climate change, water resource management, Central and Western Himalaya

INTRODUCTION

The Himalaya-Karakoram (HK) region harbours largest glacier cover outside poles. There are ~39,660 glaciers in the HK covering an area of ~42,535 km2 and an ice volume of ~3422 km3(Jackson et al., 2023). As per Geological Survey of India (GSI, 2009), there are 9,575 glaciers in the Indian part of Himalaya covering a total of 37,465 km2 of area. The huge cryospheric reserves of HK not only buffer climatic extremes but also sustain some of the world's largest river systems. Among its sub-regions, the Central and Western Himalayan region (hereafter referred to as CWH region) stands out due to its extensive glaciations, rugged topography, and pronounced climatic variability. The Indian part of CWH region contains a total of 8,965 glaciers with cumulative area of 36,536 km2 (GSI, 2009). This region serves as the headwater zone for several perennial rivers, including the Indus, Chenab, Sutlej and the Ganges, which function as lifelines for millions of people living in these basins (Immerzeel *et al.,* 2010). Beyond its role as a cryospheric stronghold, the CWH region is thus a critical freshwater source, underpinning agriculture, hydropower production, and domestic use in vast downstream areas.

Glaciers in this region act as natural water towers, storing precipitation in the form of snow and ice during colder months and releasing it seasonally as melt water. The discharge from glacier melt contributes significantly to stream flow, especially during the pre-monsoon and post-monsoon seasons when rainfall is limited and water demand peaks (Kaser *et al.,* 2010). This seasonal buffering function is essential for sustaining river flow, ensuring irrigation, and maintaining ecosystem stability during dry spells. However, the magnitude, timing, and variability of melt water discharge are intricately linked to climatic drivers such as air temperature, solar radiation, and precipitation dynamics (Fountain & Tangborn, 1985). With the Himalaya warming at a rate higher than the global average, often described as a climate change "hotspot," the urgency to understand these discharge dynamics has increased manifold (Shrestha *et al.,* 2012).

Despite its importance, the hydrological behaviour of Himalayan glaciers-particularly in the CWH region-remains poorly constrained. Several factors contribute to this knowledge gap, including the region's harsh terrain, logistical difficulties in field monitoring, sparse hydro meteorological networks, and limited availability of long-term data (Azam *et al.,* 2018). Consequently, while considerable progress has been made in assessing glacier mass balance and regional climate impacts, relatively few studies have addressed the finer-scale hydrological responses of glacier-fed catchments (Azam *et al.,* 2021). Furthermore, the interaction between seasonal climatic regimes, surface energy balance processes, and glacier hydrodynamics remains only partially understood, making projections of future water availability highly uncertain.

This lack of clarity has significant implications for downstream societies. Rising temperatures and shifts in precipitation patterns are already accelerating glacier retreat in the CWH region, altering the quantity and seasonality of melt water contributions to river systems (Sakai & Fujita, 2017). In certain catchments, enhanced melting may temporarily increase stream flow, while in others, rapid glacier shrinkage could diminish water availability in the long term. Such divergent outcomes pose challenges for agriculture-dependent economies, hydropower development, and drinking water security across densely populated lowlands (Lutz *et al.,* 2014). Moreover, abrupt changes in discharge patterns may increase the risk of extreme events such as glacial lake outburst floods, further amplifying the socio-environmental vulnerability of the region.

Given this importance, assessing the variability of glacier melt water discharge is not only a scientific imperative but also a socioeconomic necessity. A clearer understanding of the temporal and spatial dynamics of melt water will enable better forecasting of river flows and help policymakers design adaptive water management strategies. The present study aims to fill existing knowledge gaps by investigating the patterns and controlling factors of glacier melt water discharge in the CWH region. We compiled discharge data from 6 glaciers, covering most regions of the Central and Western Himalayan domain. This synthesis provides valuable insights into the dynamics of cryosphere-hydrosphere interactions in one of the world's most climatically sensitive mountain systems. The outcomes of this work are expected to support sustainable water resource management and guide climate adaptation strategies across the Himalayan River basins.

STUDY AREA

The study focuses on the Central and Western Himalaya, covering a part of Ladakh, Himachal Pradesh, and Uttarakhand, a region known for its steep topography, extensive glaciers, and diverse climatic conditions (Bolch *et al.,* 2019; Immerzeel *et al.,* 2010). This area hosts both large valley glaciers, such as Gangotri and Chhota Shigri, and smaller alpine glaciers in Ladakh and Himachal Pradesh, which act as critical water reservoirs (Kaser *et al.,* 2010). Seasonal precipitation patterns are strongly influenced by Western Disturbances in winter and the Indian summer monsoon, producing marked temporal variability in melt water discharge (Shrestha *et al.,* 2012). Glacier-fed rivers including the Chandra, Bhagirathi, Shyok, Zanskar, Gilgit, Jhelum, Chenab, Ravi, Beas, and Sutlej provide essential water for agriculture, hydropower, and domestic use, highlighting the socio-hydrological importance of this region (Lutz *et al.,* 2014).

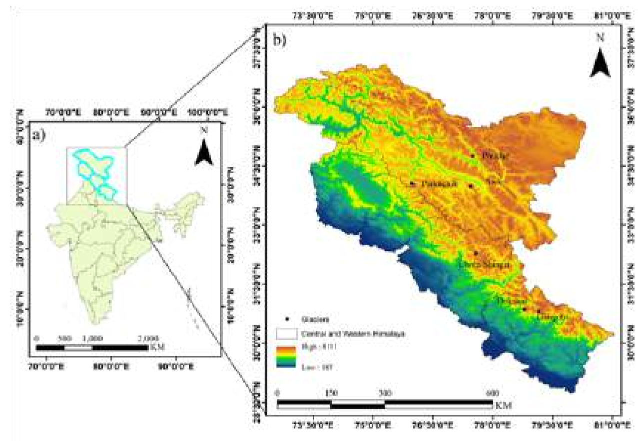

Fig. 1: Location map showing the geographical extent of the Central and Western Himalayan Region (CWH region); (b) Distribution of 6glacier sites within the CWH region.

METHODOLOGY

To assess the current status and variability of glacier meltwater discharge in the CWH region, a narrative literature review was conducted, synthesizing information from multiple sources. Relevant studies were systematically retrieved from major academic databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, using targeted keyword combinations such as glacier, glacier discharge, Western Himalaya andclimate change. The review focused on English-language publications and included peer-reviewed journal articles, technical reports, and government or institutional documents. Each study was critically evaluated for its spatial coverage, methodologicalprecision, and temporal resolution, with particular attention given to seasonal and interannual variability in meltwater discharge. Key hydrological parameters-including glacier name, river basin, mean daily discharge (m^3/s), and discharge range (m^3/s)-were compiled to build a consistent dataset. In addition, a study map was prepared in the GIS environment with digital elevation model (DEM) from Shuttle Radar Topographic Mission Version-3 to visualize the distribution of glacier sites across the region.

RESULTS

The analysis of glacier melt water discharge across the CWH region shows strong spatial and temporal variability, reflecting differences in glacier size, catchment setting and climatic condition and monitoring approaches. A state-wise comparison provides a clearer picture of how melt water contribution varies from the cold-arid basins of Ladakh to the monsoon-dominated catchments of Himachal Pradesh and Uttarakhand. Table 1 summarizes the observed and inferred melt water discharge from 6representative glaciers, showing spatial and seasonal variability across the Central and Western Himalaya.

In Ladakh, glacier-fed streams contribute modest but critical flows to the Indus basin and its tributaries. The Stok glacier, which drains through the Stok stream into the Indus, provides one of the lowest discharge values among the studied glaciers. Model simulations, supported by field calibration in 2018–2019, indicate an average discharge of approximately 0.31 m³/s, with variations ranging from 0.3 to 0.7 m³/s during the 2003–2019 period (Soheb *et al.,* 2024). Despite its small magnitude, this flow is significant for sustaining water availability in an otherwise arid environment. The Parkachik glacier in the Suru Valley of Ladakh stands in sharp contrast to Stok, generating substantially higher runoff. Melt-season monitoring between 2017 and 2023 shows a mean daily discharge of about 5.0 m³/s. Seasonal and interannual variability is evident, with flows as low as 3.5 m³/s in 2021 and peaks reaching 10.0 m³/s in 2023 (Yadav *et al.,* 2025). These patterns illustrate how glacier-fed rivers in Ladakh respond sensitively to changing climatic conditions, particularly temperature and snowfall variability, making Parkachik one of the most important regional water sources. The Phuche glacier in the Upper Gangles tributaries, reflects an intermediate discharge regime compared to Stok and Parkachik. Observations during May-October 2010 indicate melt water contributions ranging from 0.4 to 2.15 m³/s (Priya *et al.,* 2016). The relatively low values are consistent with its smaller glacierized catchment and the cold-arid environment, where reduced precipitation limits meltwater generation. Collectively, Ladakh glaciers demonstrate a wide discharge spectrum, from less than 1 m³/s in smaller catchments to nearly 10 m³/s in larger ones, highlighting the strong dependence of water yield on local glacier size and valley characteristics.

Moving westward into Himachal Pradesh, the Chhota Shigri glacier represents one of the most extensively monitored benchmark glaciers in the Indian Himalaya. Long-term discharge records covering 2010–2016 reveal a mean daily discharge of about 6.2 m³/s. However, fluctuations are substantial, ranging from as little as 0.3 m³/s to as much as 17.4 m³/s during the ablation period (May-October) (Mandal *et al.,* 2020). These variations highlight the combined influence of diurnal melt cycles and monsoon rainfall, which amplify runoff variability. The Chhota Shigri data set is critical for understanding discharge dynamics under a transitional climate regime where both westerly-driven snowfall and summer monsoon rains play roles in shaping hydrological output.

In Uttarakhand, the Gangotri and Dokriani glaciers provide important insights into melt water discharge within the Ganga basin. The Gangotri glacier, one of the largest in the Himalaya, contributes very high melt water volumes to the Bhagirathi River. Although discharge is often inferred indirectly from solute flux studies, estimates indicate values of about 28 ± 1.9 m³/s across the pre-monsoon, monsoon, and post-monsoon phases (Priya et al., 2016). In comparison, average discharge was reported as 37 m³/s, with a range of 29–50 m³/s during May–October 2000–2003 (Singh *et al.,* 2006).These figures highlight Gangotri's role as a dominant hydrological contributor, not just within Uttarakhand but across the entire Ganga basin.The Dokriani glacier, by contrast, provides more moderate flows but has been studied in greater hydrological detail. During the 1994 melt season,

Table 1: Glacier melt water discharge in the Western Himalaya

Glacier Name	River Basin / River	Region	Average Discharge (m³/s)	Discharge Range (m³/s)	Time Period Monitored	Reference
Stok	Stok stream (drains to Indus River)	Ladakh	~0.31 m³/s	~0.3–0.7 m³/s	2003–2019 (model simulation calibrated with field data 2018–2019)	Soheb *et al.,* (2024)
Parkachik	Chilling Nala (Suru River)	Ladakh (Suru Valley)	≈ 5.00 m³/s	3.5 – 10.0 m³/s (lowest in 2021, highest in 2023)	2017–2023 (melt-season daily mean discharge, June–September)	Yadav *et al.,* (2025)
Phuche	Tributaries in Ladakh (Upper Gangles region)	Ladakh	0.4-2.15 m³/s	—	May-October, 2010	Priya *et al.,* (2016)
Chhota Shigri	Chandra River (Chenab basin)	Himachal Pradesh	~6.2 m³/s (mean daily)	0.3-17.4 m³/s	Ablation seasons May-Oct, 2010-2016	Mandal *et al.,* (2020)
Gangotri	Ganga basin	Uttarakhand (Garhwal)	28 ±1.9 m³/s; 37 m³/s	23.3-82.5 m³/s; 29-50 m³/s	May-October 2000-2003	Priya *et al.,* (2016); Singh *et al.,* 2006
Dokriani	Ganga basin	Uttarakhand (Garhwal)	2.4-8.4 m³/s	—	May -October 1994	Hasnain & Thayyen, (1999).

discharge values ranged between 2.4 and 8.4 m^3/s from May to October (Hasnain & Thayyen, 1999). The seasonal pattern reflects pre-monsoon snowmelt, monsoon-driven peak discharges, and declining flows in the post-monsoon phase. While smaller than Gangotri, Dokriani's record is valuable for understanding glacier runoff processes in medium-sized Garhwal catchments.

Collectively, these results reveal distinct regional contrasts. Glaciers in Ladakh, located in cold-arid terrain, generally yield lower discharges, except for the relatively large Parkachik glacier. Himachal Pradesh's Chhota Shigri provides intermediate to high discharge with strong variability linked to monsoonal influence. In Uttarakhand, the Gangotri glacier dominates with very high melt water contributions, while Dokriani illustrates intermediate flows shaped by seasonal melt–rainfall interactions. This gradient from Ladakh through Himachal to Uttarakhand highlights the interplay of glacier size, regional climate, and monsoon influence in controlling Himalayan melt water discharge.

DISCUSSION

The comparison of glacier melt water discharge across the Western Himalaya demonstrates how regional settings, climatic controls, and glacier characteristics shape hydrological responses. The results show that while all glaciers contribute to sustaining downstream flows, the scale and variability of their discharge differ markedly between Ladakh, Himachal Pradesh, and Uttarakhand.

In Ladakh, the cold-arid climate limits snowfall and rainfall, resulting in relatively modest discharge values. The Stok glacier, for example, provides only a fraction of a cubic meter per second, yet its contribution is locally vital, as it sustains water resources in one of the driest parts of the Himalaya (Soheb *et al.,* 2024). By contrast, the Parkachik glacier illustrates how larger ice masses in the same region can supply substantially higher flows, often exceeding 5 m^3/s and even reaching 10 m^3/s in wetter years (Yadav *et al.,* 2025). These findings highlight that, within Ladakh, catchment size and ice volume are primary controls on runoff. Phuche glacier, with intermediate discharge levels, further supports this interpretation by showing that smaller glaciers generate proportionally lower outputs (Priya *et al.,* 2016). The variability across Ladakh glaciers suggests that future changes in glacier area or snow accumulation will directly influence local water security.

In Himachal Pradesh, discharge patterns from the Chhota Shigri glacier reveal a transitional regime where both westerly winter snowfall and summer monsoon rainfall play major roles. The glacier shows high variability, with flows fluctuating between less than 1 m^3/s and more than 17 m^3/s during the ablation season (Mandal *et al.,* 2020). This wide range reflects not only diurnal melt cycles but also the amplification of runoff during monsoon storms. Unlike Ladakh, where meltwater is almost exclusively from glacier and snow melt, the mixed climatic influences in Himachal create more dynamic and less predictable discharge conditions. These results underline the importance of long-term hydrological monitoring in transitional zones, as they may be more sensitive to changes in both monsoon intensity and snowfall patterns.

In Uttarakhand, the Gangotri and Dokriani glaciers highlight the importance of scale in determining hydrological contributions. Gangotri, one of the largest glaciers in the region, generates substantial melt water flows, with discharge estimates of 28 ± 1.9 m^3/s (Priya *et al.,* 2016) and an average of 37 m^3/s (Singh et al., 2006). The glacier's discharge varies considerably, ranging from 23.3 to 82.5 m^3/s and 29 to 50 m^3/s, reflecting a clear seasonal pattern characterized by peak flows during the monsoon and reduced flows in the post-monsoon period. Such magnitudes make Gangotri a crucial source for the Bhagirathi River and, by extension, the entire Ganga basin. The Dokriani glacier, though smaller, provides valuable insights because of its detailed discharge records. Its flows, ranging between 2.4 and 8.4 m^3/s, follow a clear seasonal rhythm, with peak discharge during the monsoon and reduced flow in the post-monsoon period (Hasnain & Thayyen, 1999; Priya *et al.,* 2016). Together, Gangotri and Dokriani demonstrate how large glaciers dominate regional hydrology, while medium-sized glaciers serve as representative sites for studying seasonal hydrological processes.

Across the Western Himalaya, a clear gradient emerges. Glaciers in Ladakh generally deliver lower discharges, reflecting cold-arid conditions and smaller catchments, with Parkachik standing out as an exception due to its size. In Himachal Pradesh, glaciers produce moderate to high discharges, but with strong variability tied to the interaction of monsoon rains and melt water processes. In Uttarakhand, discharge values are highest, especially from Gangotri, highlight the major role of glacier melt in sustaining perennial river systems like the Ganga.

These findings emphasize that regional climate, glacier size, and catchment conditions jointly determine the hydrological role of glaciers. Therefore, targeted monitoring should be initiated for different size-types of glaciers to understand the variability in the production of melt water discharge. As climate change continues to alter snowfall, rainfall, and temperature regimes across the Himalaya, the sensitivity of glacier discharge highlighted in this study suggests that downstream water availability will be unevenly affected. Regions like Ladakh, where small glaciers already contribute marginal flows, may face the most immediate water stress, while large glaciers such as Gangotri will continue to buffer river discharge in the near term but remain vulnerable in the long run. Further, it is notable that glacier streams with high base flow contribution can maintain flow even when glacier melt decreases, due to groundwater buffering. On the contrary, channels with low base flow inputs are more vulnerable to drying during periods of low melt or prolonged drought. Markedly, most of the reported discharge measurements for glacier-dominated catchments in the CWH region are for summer seasons which are often melt-driven with relatively low base flow. During winter or low-melt seasons, base flow dominates, leading to higher base flow contribution. Hence, the knowledge of base flow contribution helps separate melt water contributions from groundwater or delayed flow. However, there is a poor knowledge of the base flow contribution to the total discharge which should be targeted in future research.

CONCLUSION

The analysis of glacier melt water discharge across the Central and Western Himalayan region highlights significant spatial and seasonal variability, shaped by regional climate, glacier size, and catchment characteristics. Ladakh glaciers, situated in a cold-arid environment, generally produce low to moderate flows, with the Stok and Phuche glaciers contributing minimal discharge, while larger glaciers such as Parkachik provide comparatively higher runoff. In Himachal Pradesh, glaciers like Chhota Shigri exhibit intermediate to high discharges, strongly influenced by both westerly snowfall and summer monsoon precipitation, resulting in pronounced seasonal and interannual variability. In Uttarakhand, large glaciers such as Gangotri dominate regional hydrology, delivering substantial melt water to the Bhagirathi River, whereas medium-sized glaciers like Dokriani provide valuable insights into seasonal melt dynamics. Across the Western Himalaya, a clear gradient emerges: from the low discharges of cold-arid Ladakh, through the moderate to highly variable flows in Himachal Pradesh, to the high discharge volumes in Uttarakhand, reflecting the combined influence of glacier size and climatic conditions. We recommend that targeted monitoring should be initiated for different size type of glaciers to understand the variability in the production of melt water discharge. Further, the relatively poor knowledge of base flow contribution in total discharge hampers a clear understanding of melt water variability which should be inherently reported to quantify aquifer contributions.

These patterns highlight the critical role of glaciers in sustaining downstream water resources, particularly in arid and semi-arid regions. The study also highlights the vulnerability of Himalayan hydrology to climate change, as alterations in temperature, precipitation, and glacier mass balance are likely to impact the timing and magnitude of melt water availability. Smaller glaciers in Ladakh may face immediate reductions in water supply, whereas large glaciers such as Gangotri may continue to buffer river discharge in the short term but remain at risk under long-term climatic shifts. Overall, understanding these regional differences is essential for water resource management, climate adaptation strategies, and predicting the future hydrological impacts of glacier change in the Central and Western Himalaya.

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EXPLORING GEOTHERMAL ENERGY FOR A SUSTAINABLE FUTURE IN LADAKH, NORTHWESTERN HIMALAYA

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ABSTRACT

Geothermal energy, derived from the Earth's internal heat, offers a clean, renewable, and reliable alternative to fossil fuels. In Ladakh, one of the coldest inhabited regions on the Earth. energy access is severally constrained by remoteness, harsh climatic conditions, and high reliance on imported fuels. Traditional energy sources such as firewood and cow dung have largely been replaced by diesel and petrol, leading to rising costs and environmental degradation. While solar and hydropower contribute to the region's energy supply, both face seasonal limitations, making geothermal resources particularly valuable. Located within the tectonically active Himalayan Geothermal Belt, Ladakh hosts several promising sites, including Puga, Chumathang, and Nubra, with Puga identified as the most viable for power generation. Harnessing these geothermal resources can ensure year-round electricity, space heating, and agricultural support, while also reducing carbon emissions and dependence on fossil fuels. Recent initiatives, including ONGC's geothermal project at Puga, highlight growing recognition of this resource's potential. Beyond energy production, geothermal applications could enhance tourism, agriculture, and socio-economic development in this ecologically fragile mountain region. Thus, geothermal energy represents a transformative pathway toward energy security, sustainable development, and carbon neutrality in Ladakh.

Key words: Geothermal energy, Ladakh Himalaya, renewable energy, Puga geothermal field, sustainable development, energy security

INTRODUCTION

Geothermal energy refers to the heat stored beneath the Earth's crust, primarily generated by the slow radioactive decay of elements and the residual thermal energy from the planet's formation. This heat escapes naturally through hot springs, steam vents, and volcanic activity. Humans harness this underground heat by extracting steam or hot water from geothermal reservoirs to produce electricity, heat buildings, or support industrial and agricultural applications. Unlike fossil fuels, geothermal energy is renewable, has a stable supply throughout the year, and produces very low greenhouse gas emissions, making it an important sustainable energy source (DiPippo, 2015; Lund *et al.,* 2011).

The Ladakh Himalaya, located in the north-western Indian Himalayas, is one of the coldest inhabited regions of the world, characterized by long winters, sparse vegetation, and very significant and high dependence on imported fossil fuels for energy. Electricity supply in the region is inadequate and often interrupted, while the cost of transporting conventional fuels from the plains is extremely high due to remoteness and harsh terrain (Agarwal *et al.,* 2020). In this context, geothermal energy emerges as a crucial renewable resource.

Ladakh lies within a tectonically active zone of the Trans-Himalaya, where geothermal manifestations such as hot springs and thermal springs are widespread (Craig *et al.,* 2013). These natural occurring geothermal reservoirs can provide a locally available, clean, and sustainable source of energy for electricity generation, space heating, and greenhouse-based agriculture, which is particularly essential for food security in this high-altitude desert (Chandrasekharam,2002).

Utilizing and harnessing geothermal resources in Ladakh would not only reduce dependency on fossil fuels but also help mitigate carbon emissions in this ecologically fragile mountain environment. Moreover, geothermal-based heating and power can provide a reliable year-round supply of energy, unlike solar and hydropower, which face seasonal limitations (Nakada *et al.,* 2014). Hence, geothermal energy holds great promising pathway for achieving both sustainable development and energy security in the Ladakh Himalaya.

ENERGY RESOURCES IN THE EARLY 1980s

During the early 1980s, Ladakh was not connected to the national electricity grid. The local population primarily relied on traditional sources of energy such as cow dung and firewood, which were used for both cooking and heating. These resources were largely sufficient to meet the community's energy requirements at that time. Traditionally Ladakhi houses were constructed usingmud bricks and characterized by small doors and windows, were designed to minimize heat loss and provide natural insulation against the region's harsh climatic conditions.

Over time, however, fossil fuels gradually emerged as the dominant source of energy, marking a shift from traditional practices to modern energy dependence.

MODERN HOUSE TECHNIQUES IN LADAKH

Fig. 1: (a) Ladakhi traditional mud brick house (b) Cow dung and woods used as energy source

The opening of Ladakh to tourism in 1971 brought new needs and expectations to the region. Tourists staying in hotels began to demand facilities such as hot running water and uninterrupted electricity. To meet these demands, many modern houses are now being constructed with concrete and glass. However, such designs are neither eco-friendly nor suitable for the fragile Himalayan environment. These structures require greater heating, which in turn increases dependence on fossil fuels. As a result, the region faces rising environmental degradation and pollution due to increased emission, deforestation and growing economic cost associated with fossil fuel dependence.

SOLAR ENERGY IN LADAKH

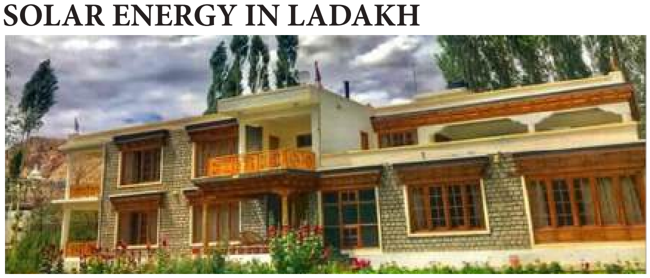

Fig. 2: Modern house in Ladakh with large doors and windows

Over the past two to three decades, solar energy has emerged as one of the most extensively utilized renewable energy sources in Ladakh. Owe to its high altitude and geographical setting, Ladakh is often referred to as the "roof of the world" and receives abundant solar radiation with clear skies for most of the year, making it highly suitable for the deployment of solar energy technologies (Kapoor *et al.,* 2014; Rahim, 2024). In remote villages where access to the National Power Grid is limited or entirely absent, solar photovoltaic (PV) panels and solar cookers serve as vital energy sources for meeting electricity and cooking needs (NITI Aayog, 2019). However, these systems face limitations, particularly during cloudy conditions and in the winter months, when reduced sunlight and battery storage issues hinder their effectiveness. An important innovation in this context is the Solar Passive House, which harnesses solar energy for heating and insulation without the use of mechanical systems. These houses are designed to retain heat in winter and minimize overheating in summer, thereby reducing reliance on fossil fuels (Mussard, 2017). Despite these advancements, the growing energy demand and high consumption patterns remain a challenge for ensuring long-term sustainability in the fragile Himalayan environment.

HYDROPOWER IN LADAKH

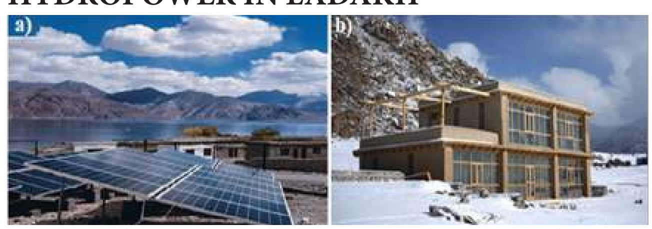

Fig.3: (a) Solar Panels installed at Pangong (b): Passive Solar House

The Nimoo Basgo Hydroelectric Project is a run-of-the-river scheme constructed on the Indus River at Alchi village, approximately 75 km from Leh in the Union Territory of Ladakh. The project was formally approved on 1 July 2001, while construction commenced on 23 September 2006. It consists of a 57 meters high concrete dam with five spillway blocks, each 13 meters wide and designed with an ogee profile to regulate water flow (NHPC, 2012). Despite its significance in supplying renewable energy to Ladakh, the project faces seasonal challenges. During the harsh winter months, the discharge of the Indus River is substantially reduced due to freezing conditions, and consequently, power generation drops to nearly one-third of the installed capacity, producing only 11–15 MW of electricity. This reduced output is inadequate to meet the region's rising energy demand in winter, which increases significantly because of heating requirements (Wangchuk, 2020).

GEOTHERMAL ENERGY IN LADAKH

Ladakh lies within the Himalayan Geothermal Belt a tectonically active region, which hosts several promising

Fig. 4: Nimoo-Basgo Power Project at Alchi

geothermal fields. The Union Territoryhome has three major geothermal sites (Puga, Chumathang, and Nubra) that have attracted scientific and developmental interest (Arya & GSI, 2020). Among these, the Puga geothermal field is considered the most potential-rich, with studies indicating that it could sustain a 20 MW power plant at the currently accessible drilling depth of about 250 meters (Gupta & Roy, 2007). With Ladakh's gradually rising population and the rapid growth of tourism, energy requirements are expected to increase considerably in the coming years. Researchers emphasize that geothermal energy offers a reliable, renewable, and sustainable alternative to meet this growing demand while reducing dependence on fossil fuels (Wangchuk, 2020). In recognition of this potential, the Oil and Natural Gas Corporation (ONGC) has initiated steps toward developing India's first geothermal field project in Ladakh. A Memorandum of Understanding (MoU) was signed on 6 February 2021 between ONGC Energy Centre (OEC), the Union Territory of Ladakh, and the Ladakh Autonomous Hill Development Council (LAHDC), Leh, marking the beginning of geothermal field development at Puga. This project is envisioned as a milestone in building a carbon-neutral Ladakh (ONGC, 2021). Beyond its energy contribution, geothermal development is expected to play a crucial role in preserving the fragile environment of the Himalayas while also supporting local socio-economic development, particularly by generating employment and boosting regional infrastructure (Gupta & Roy, 2007; ONGC, 2021).

GEOTHERMAL APPLICATIONS IN LADAKH

At present, geothermal springs in Ladakh are primarily used for bathing and traditional therapeutic purposes, particularly in relieving joint pain and related ailments, owing to the presence of minerals such as sulfur and borax in the water (Dutta *et al.,* 2024). Beyond these current uses, geothermal energy holds significant potential for broader applications in the region. It can be harnessed for electricity generation, space heating, and even for extending the growing season of crops during harsh winters, thereby enhancing agricultural productivity (Gupta & Roy, 2007).

Fig. 5: MoU signed between ONGC and UT Ladakh

Additionally, the utilization of hot water resources could promote winter sports and tourism in areas such as Changthang, which lies along Ladakh's border regions. This would not only encourage geotourism but also contribute to the socio-economic upliftment of local communities living under challenging topographical and climatic conditions (Lund & Boyd, 2016).

Furthermore, geothermal heat pump (GHP) technology offers an efficient and sustainable way to regulate indoor temperatures. Commercial establishments, government offices, military installations, and critical infrastructure such as Leh Airport could be effectively heated during severe winters and cooled in summer by integrating geothermal systems, reducing dependence on fossil fuels and imported energy (Barbier, 2002).

CONCLUSION

Geothermal energy holds the potential to play a transformative role in addressing the persistent energy challenges of Ladakh, particularly in its remote and strategically important border regions. Unlike solar and hydropower, which are subject to seasonal and weather-related fluctuations, geothermal resources can provide a stable, round-the-clock power supply throughout the year. This reliability makes geothermal

Fig. 6: Puga Hot Spring contains sulfur and borax

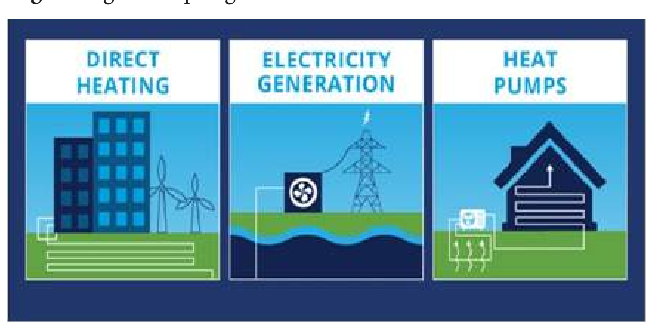

Fig. 7: Three major uses of Geothermal Energy

energy a key solution for ensuring energy security in the Union Territory. Harnessing this renewable resource would not only reduce Ladakh's dependence on costly imported fossil fuels but also pave the way for a self-reliant and resilient local economy. The establishment of geothermal plants would generate new employment opportunities, support skill development, and create allied industries, thereby directly contributing to the Government of India's "Vocal for Local" initiative. This, in turn, would improve the socio-economic conditions of the communities living in some of the harshest climatic and geographical settings. Moreover, geothermal energy is widely recognized as one of the cleanest and most sustainable forms of renewable energy. Its adoption would significantly cut greenhouse gas emissions, promote low-carbon development, and move Ladakh closer to the vision of becoming a carbon-neutral territory. By integrating geothermal power into its energy mix, Ladakh can position itself as a model for sustainable development in high-altitude, ecologically fragile mountain regions, while also strengthening national energy security. This shift would also entrance national energy security while preserving the unique environmental and cultural heritage of the Himalayas.

ACKNOWLEDGEMENTS

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MAPPING SOCIOECONOMICS DIVERSITY LANDSCAPE: INSIGHTS FROM FOUR VILLAGES, GUNJUNG, JATINGA, WADRENGDISA & LONGMA IOF DIMA HASAO DISTRICT OF ASSAM, INDIA

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ABSTRACT

Nestled amidst the majestic Barail Ranges, the four villages under study are characterized by a hilly landscape, a distinctive feature that sets them apart from the rest of Assam. The district itself, situated at an elevation of 513 meters, is the only hilly region in the state, surrounded by the towering Barail mountain ranges, creating a unique topographical setting for these rural communities. The purposes of this study are to ascertain the people's living and working conditions. The goal of this research is to fully understand the socioeconomic environment. The primary data sources for the study are gathered with the aid of both qualitative and quantitative methodologies. Some visual statistical methods are used to represent the state of this area. Investigating the socioeconomic situation of these places in terms of their population, employment, education, income, housing characteristics, and government programs is crucial. A plethora of natural resources are at their disposal for the building of sustainable livelihoods. As a result, an effort has been undertaken to examine these communities' socioeconomic situation in this article.

Key words: Socioeconomic survey, Rural communities of Hilly region, Barail Ranges, Comparative analysis

INTRODUCTION

A comprehensive socioeconomic survey has been carefully conducted across four remote villages nestled in the hilly terrain of Assam. This groundbreaking initiative, supported by local Panchayat and other resourceful entities, aims to unravel the intricate socioeconomic realities that shape the lives of the villagers. Employing a blend of qualitative and quantitative approaches, including carefully designed questionnaires, the survey delves deep into the lived experiences and nuances of these communities. As the data unfolds, it promises to provide profound insights into the challenges, aspirations, and trajectories that define the socioeconomic landscape of these hilly regions. This endeavour underscores an unwavering commitment to understanding the complex tapestry of human experiences, paving the way for informed decisions and positive transformations.

OBJECTIVES

Depending on the particular environment and survey goal, a socio-economic survey may have several objectives. Nonetheless, the following are some typical goals that are usually followed in these kinds of surveys:

Recognizing Demographics: Age, gender, education level, employment, income, and household size are just a few of the variables that socioeconomic surveys frequently seek to collect data on. This information is useful in determining the target population's social and economic makeup.

Evaluating Economic Conditions: Information on a range of economic topics, such as income inequality, rates of poverty, employment trends, industry composition, and accessibility to financial services, may be gathered through the survey. The analysis of the financial health of people and communities is aided by this data.

Determining Social Indicators: Socio-economic surveys frequently ask about social indicators, including housing, healthcare, education, and access to necessities like water and sanitation. These metrics aid in assessing the population under study's social progress and standard of living.

Analyzing Inequalities and Disparities: Surveys can provide information about inequalities and disparities within a population by gathering data on income, education, and other socioeconomic indicators. For policymakers to create focused actions and programs to close these gaps, they need this information.

RATIONAL OF THE STUDY

There are several reasons to which make it essential to conduct socioeconomic study of a village which note the complications and exclusive characteristics of rural environment. The cohesive interrelationship among socioeconomic factors, natural resources and community dynamics has a substantial role in formatting the payoff of rural initiatives and policies. Because of that, in-depth understanding of these factor is integral for impactful planning and intervention strategies.

Fundamentally in many countries, basic administrative and socioeconomic units have a base in villages which are going to influence the effective implementation of broader sustainable development goals (SDGs). Recognizing the distinct characteristics of socioeconomic conditions of rural areas can aid policy makers and stakeholders to make informed decisions and ensure rural advancement can integrate itself into broader national sustainability policies as these are often confronted with unique opportunities and challenges (He *et al.,* 2021).

Furthermore, socioeconomic studies also shed light on various aspect of rural life, such as access to resources, educational needs, health disparities and poverty levels. As research suggests that high socioeconomic deprivation has been often linked with adverse health outcomes including early mortality (Lamnisos *et al.,* 2019). So, it is essential to understand socioeconomic profile to design health intervention to suit local needs. In addition to this, better targeted interventions can be done by studying various quantitative indicators which represent the complexities of rural communities (Lalloue *et al.,* 2013).

Socioeconomic studies also delve into ecological and agricultural practices to improve farmers livelihoods by encouraging sustainable agricultural practices (Zhang *et al.,* 2020). By acknowledging differences in socioeconomic status within rural communities we can help improve resiliency in those communities to counter migration pressures (Wilson *et al.,* 2018). While our studies do not explicitly address issues of participation or governance, they do provide information to improve community participation and governance. For example, good governance in tourism enables greater changes in rural economies (Keyim, 2017). Maintaining this focus on empowerment through tourism and economic diversification is important for rural areas where decline is occurring (Priatna *et al.,* 2021).

Conducting a socioeconomic study of a village is important to recognize the complex interactions between economic activities; social structures and environmental conditions; and this helps to identify the outcomes that shape rural livelihoods. Socioeconomic studies provide critical information related to economic levels, market and other resources; demographic characteristics; and overall rural community quality of life. The importance of conducting socio-economic study of a village can be organized around the following key areas:

Understanding Rural Livelihoods and Economy

Rural economies largely depend on agriculture, allied and natural resource-based activities, and traditional craft activities. Through a socio-economic study, we can evaluate income sources, sorting of employment, landholding sizes, and share of agricultural and non-agricultural activities in the village economy (Ellis, 1999). Understanding these areas provides information to policymakers and development practitioners by allowing them to develop specific interventions that improve rural incomes and employment.

Evaluation of Social & Demographic Characteristics

The individual demographic characteristics such as population size, age structure, literacy rates, gender structure, etc., are significant for the overall planning of development actions (Chambers, 1983). A socioeconomic study allows for understanding the social stratification, caste systems, and cultural attributes of the community and their implications for both decision-making and resource allocation, and community interaction.

Identification of Developmental Needs and Gaps

Socioeconomic studies identify gaps in infrastructure, health services, education and the availability of basic needs, as well as how access rates for clean water, sanitation, electricity and modes of transport vary, as these are all essential components for enhancing living conditions in rural areas (World Bank, 2007). This type of information is useful for directing investments and government inattention to areas in need of attention and development.

Awareness of Land Use and Natural Resource Management

Rural communities' land and natural resources use and management affects their economic viability and environmental quality. A socioeconomic study shows land ownership patterns, cropping systems, irrigation status, and reliance on forests and common property resources (Bebbington, 1999). These are useful identifying issues that require sustainable land management and conservation programs.

Assessing Impact for Government Strategies and Policies

Government strategies and through government policies can all have direct implications on village economies. Socioeconomic studies help in evaluating the effectiveness and reach of these programs which could allow for policy implications to change or new programs to be implemented (Scoones, 1998).

Participatory Development Planning

Participatory rural appraisal (PRA) methods combined with socioeconomic research can give people in their villages a voice that empowers them to express their needs and priorities. Involving villagers in the collection and assessment of the data increases community ownership of development processes and leads to sustainable and inclusive development (Chambers, 1994).

CONCLUSION

A socioeconomic study of a village is a critical first step to understanding and advancing the quality of life for rural people. Socioeconomic studies identify economic constraints, social inequalities, and other development deficits that will comprise the basis of evidence-based policymaking for sustainable rural development. Findings from socioeconomic studies can, and should, inform the strategies of local governments, non-governmental organizations, and other researchers for developing resilient economies, equitable societies, and sustainable environments.

Conceptual Framework

Independent Variables Dependent Variable

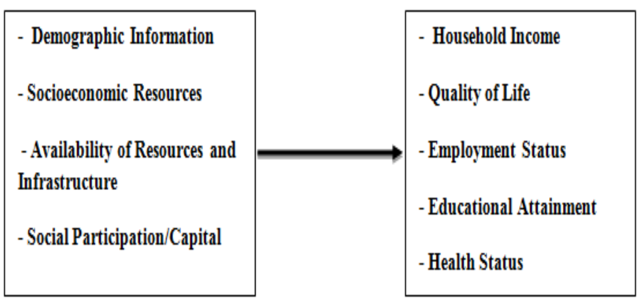


Fig. 1: Conceptual Framework

RESEARCH METHODOLOGY

The multifaceted methodology employed in this study draws upon established frameworks and best practices in the field of socioeconomic research. The qualitative component, comprising in-depth interviews and focus group discussions, aligns with the principles outlined by renowned scholars such as Kvale (1996) and Morgan (1997), who emphasize the importance of capturing rich, contextualized narratives. Furthermore, the quantitative aspect, anchored in a carefully designed questionnaire, finds its methodological underpinnings in the works of esteemed survey researchers like Floyd J. Fowler Jr. (2014) and Robert *et al.,* (2009). These seminal texts provide guidance on constructing valid and reliable survey instruments, ensuring the integrity and representativeness of the collected data.

Additionally, the integration of qualitative and quantitative approaches resonates with the mixed-methods paradigm advocated by prominent methodologists such as Creswell and Plano Clark (2018), who emphasize the synergistic potential of combining complementary data sources for a comprehensive understanding of complex social phenomena.

By drawing upon these well-established methodological frameworks and scholarly references, the researchers have strengthened the rigor and credibility of their socioeconomic survey, ensuring that the findings accurately reflect the multidimensional realities of the target communities.

AREA OF STUDY AND LOCATION

The study focuses on conducting a socioeconomic survey across four villages - Gunjung, Jatinga, Wadrengdisa, and Longma I - located in the Dima Hasao district of Assam. This autonomous hill district, known for its picturesque hill station Haflong at 513 meters elevation, offers an opportunity to explore the economic prospects, social fabric, and resilience of the communities residing in the undulating terrain.

Despite being a tourist paradise, these villages allow for a deeper understanding of the multidimensional stories and lived realities that define the socioeconomic landscapes of Assam's hill-dwelling populations. The villages are well-connected by state highways, making accessibility easier.

The Dima Hasao district lies at 25.3478°N 93.0176°E, with an average maximum temperature of 24°C-30°C and a minimum of 10°C-14°C. Gunjung is situated 30km from Haflong, Jatinga is inhabited by Khasi-Pnar tribes at 25.1138°N and 92.9438°E, Wadrengdisa is 8km from Maibang and 57km from Haflong, while Longma I is in the Mahur subdivision. The region is well-connected to major cities by state highways, with New Haflong Railway Station as the major railway station and Silchar Airport about 100km from Haflong.

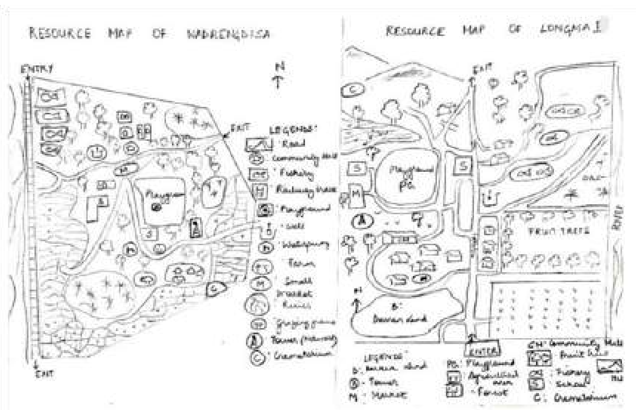
SOURCE OF DATA

The data has been collected through a structured questionnaire and personal door-to-door interviews. For the collection of qualitative data, like quality of drinking water, quality of the road, housing pattern which were obtained from the village after interaction with the villagers.

RESOURCE MAP

A resource map for a village in a socioeconomic survey visually depicts its assets and resources, both tangible and intangible. It provides insight into the village's socioeconomic conditions, aiding researchers and policymakers in understanding its strengths, weaknesses, opportunities, and threats. This knowledge guides the formulation of development strategies, addresses disparities, and enhances community well-being. Moreover, it identifies areas needing intervention and investment for sustainable growth and improved quality of life. The creation of a resource map by a student researcher proved to be a valuable tool for collecting data in a socioeconomic survey conducted within a village setting (Figure 2).

RESOURCE MAP OF GUNJUNG & JATINGA VILLAGES



RESOURCE MAP OF WADRENGDISA AND LONGMA I VILLAGES

Fig. 2: Resource maps of studied villages

SAMPLE DESIGN

Purposive sampling methods were employed to conduct a survey across all communities. Every single one of the communities' 100 households was chosen at random. Data were gathered through door-to-door visits and interactions with every household member. The information gathered was used to assess many factors, including landholdings, income, educational attainment, population, medical facilities, water sources, and conflicts with wildlife. The three languages spoken in the village were Hindi, English, and the local dialect, Dimasa.

DATA ANALYSIS

Microsoft Excel was used to evaluate the data that was gathered from the chosen hamlet. A variety of data about the villagers' social and economic circumstances were gathered. Additionally, both the quantitative and qualitative data are analyzed .The data gathered on a variety of criteria, including the sex ratio, land use pattern, land holding, occupations, literacy rate, and other infrastructures like roads, etc., were analyzed using mathematical operations like percentages and averages.

RESULTS

Demographic Status

Demography is the study of human populations, focusing on their size, structure, and dynamics. It examines various aspects of population such as birth rates, death rates, migration patterns, age distribution, and factors influencing population change over time and also enabling us to develop effective strategies to address social, economic, and developmental challenges.

Table 1: Demographic status of the study area

S. No	Villages Name	Total Population	Male	Female	Literacy Rate
1	Gunjung & Jatinga	3542	45%	55%	92.30%
2	Wadrengdisa & Longma I	107	52%	48%	89.45%

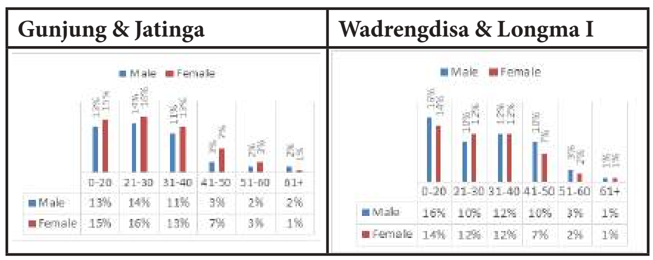


Fig. 3: Comparative analysis of age profile of the study area

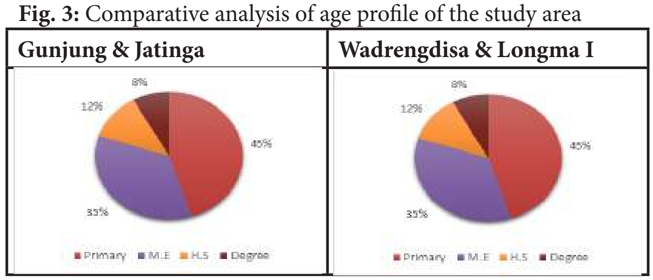


Fig. 4: Comparative analysis of educational status of the study area

Table 2: Educational establishments in the study area

Villages	Primary Schools	M. E. Schools	Secondary Schools
Gunjung & Jatinga	04	02	02
Wadrengdisa & Longma I	02	01	01

Occupation structure (Main source of Household income, Income groups, Expenditure)

Occupation structure refers to the distribution of individuals across different types of employment or occupations within a population, providing insights into the composition of the workforce, the types of jobs individuals are engaged in, occupational categories, employment patterns, and skill levels, main sources of household income, income groups, and expenditure patterns.

QUALITY OF RESIDENCE

The quality of residence refers to the characteristics and conditions of a person's living environment, encompassing various factors that contribute to the overall well-being,

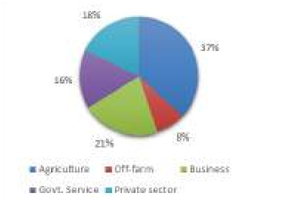
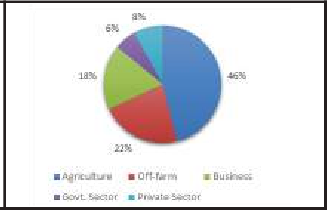
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 5: Major sources of income in study area

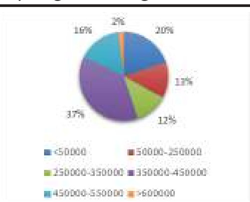
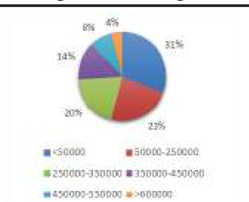
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 6: Income groups (in Indian Rupee) of the study area

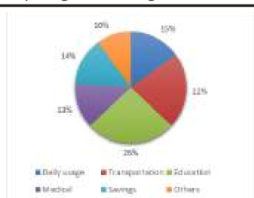
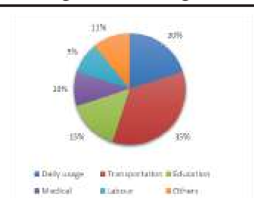
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 7: Household Expenditure (in Indian Rupee) in the study area

comfort, and suitability of a dwelling, playing a significant role in individuals' quality of life and impacting their physical health, mental well-being, and overall happiness.

MEDICAL FACILITIES

Medical facilities are institutions or locations where healthcare services are provided to individuals seeking medical treatment, diagnosis, prevention, or rehabilitation. These facilities play a crucial role in promoting public health, providing necessary care, and addressing the healthcare needs of communities.

Table 3: Medical Facilities

S. No	Type	Village	Establishment in Numbers
1	Primary Health Centre	Gunjung	01
2	State run Dispensary	Jatinga	01

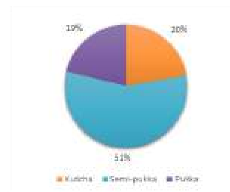
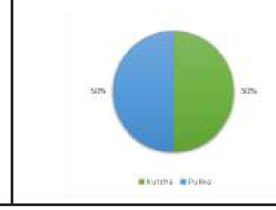
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 8: Quality of Residence

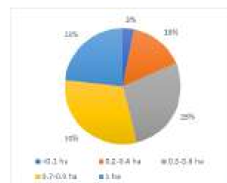
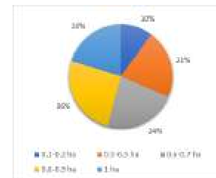
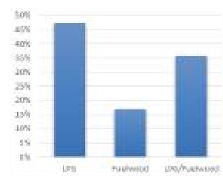
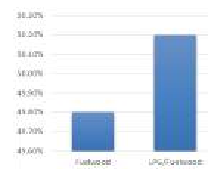
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 9: Landholding status of the study area

Fuel Type used: (Text)





Land Holding Status

"Land holding status" often refers to a piece of land's ownership or tenure status. It identifies the formal or informal claims that a person or group of people or other entities have to a certain piece of land. The legal framework, patterns of land tenure, and property laws of a nation can all affect the land holding status."

Land-Use System

A land use system is a means of managing and using land for different uses, activities, or functions. Incorporating social, economic, and environmental factors, it includes the procedures and arrangements that determine how land is allotted and utilized. The overall landscape and how it affects the community and natural resources are determined by land use systems. Based on elements such as geographic location, climate, cultural norms, and governmental legislation, land use systems can be diverse and drastically different.

Potential Impacts of Hazards

The research area is susceptible to a multitude of natural hazards. Landslides pose the most widespread threat, causing potential damage to infrastructure (communication networks, residential, commercial, and industrial),

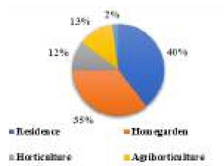
Gunjung & Jatinga	Wadrengdisa & Longma I
	

Fig. 10: Prevalent land use systems in the study area

agriculture, irrigation and drinking water systems, power supplies, livestock, and natural ecosystems (forests and orchards) across the entire district. Flash floods present a localized danger in Mahur town and Maibang, threatening lives, livestock, crops, and infrastructure. Earthquakes are a further district-wide concern, jeopardizing both life and property.

SWOT ANALYSIS

Gunjung and Jatinga	Wadrengdisa and Longma
STRENGTHS	**STRENGTHS**
•Higher literacy rate •Availability of both Municipality and streams. •Better road connectivity. •Well aware about Forest laws	•Availability of water throughout the year •Home Garden •Orchards •Practices both Pure Agriculture and Jhum cultivation.
WEAKNESS	**WEAKNESS**
•Shortage of labour due to higher literacy rate. •Absence of Pure Agriculture. •Attack on livestock by wild animals.	•Attack on farms and fields by wild animals Absence of Medical Hospitals and Dispensaries in the village.
OPPORTUNITY	**OPPORTUNITY**
•Increase in opportunity to start new businesses. •Opportunity to provide more services in both private and public sectors. •Good road connectivity	•Eco-tourism •Employment opportunities in tourist sites
THREAT	**THREAT**
•Change in climate •Urbanization occurring at a very fast pace. •Cutting down of tress of expansion of 2lane highways.	•Increased rainfall •Soil erosion. •Land area washed off during heavy rainfall. •Damage to crops due to rainfall •Attack on livestock and agricultural produce by wild animals.

VILLAGES NEEDS ASSESSMENT: CHALLENGES AND OPPORTUNITIES

The village survey paints a picture of a community grappling with several interconnected challenges. Limited access to medical facilities casts a shadow on villagers' well-being. Furthermore, a yearning for a more robust educational infrastructure underscores the community's desire for social mobility. Transportation woes further impede progress. Damaged roads and ongoing construction create bottlenecks, hindering movement of people and goods. This is compounded by the pervasive poverty affecting a significant portion of families. Many villagers remain tethered to agriculture as their primary source of income. Housing conditions also leave room for improvement, with a prevalence of impermanent "kaccha" houses. Agricultural practices, lacking the benefits of modern technology, demand a high investment of manpower and time, further straining villagers' resources. The recent heavy rains dealt a harsh blow, washing away a significant portion of precious farmland, adding another layer of hardship. However, within these challenges lie opportunities. The demand for improved healthcare and education indicates a community with a strong desire to progress. Upgrading infrastructure, including roads, can not only ease transportation but also unlock economic potential. Encouraging the adoption of modern agricultural technologies can empower villagers to improve yields and potentially diversify their income streams. The recent loss of farmland, while devastating, may necessitate exploring alternative income sources, potentially leading to new opportunities and ventures. By acknowledging these challenges and collaborating with the community, a comprehensive development plan can be crafted, fostering a brighter future for the village.

DISCUSSION

Empowering the Village: A Multi-Pronged Approach

The path to a thriving village demands a multi-pronged approach that addresses critical needs and fosters long-term sustainability.

Strengthening the Healthcare Backbone: Attracting skilled medical professionals to rural areas is paramount. Offering financial incentives, such as signing bonuses or loan repayment programs, can bridge the gap. Additionally, telehealth infrastructure can extend the reach of specialists and provide immediate access to consultations.

Investing in the Future: Education for All: Building new schools and modernizing existing ones creates an environment conducive to learning. This coupled with scholarships and targeted educational programs, can equip the next generation with the knowledge and skills for success.

Unveiling the Road to Progress: Revitalizing transportation infrastructure is crucial. A comprehensive plan for road repair and maintenance will streamline movement of people and goods, unlocking economic potential. Additionally, exploring alternative transportation options, like public buses or subsidized fuel for shared taxis, can further enhance accessibility.

Breaking the Cycle of Poverty: A multifaceted approach is needed to tackle poverty. Implementing employment generation schemes can provide immediate income opportunities. Vocational training programs empower individuals to develop marketable skills and secure better-paying jobs.

Building a Secure Future: Sustainable housing is a cornerstone of a healthy community. Providing subsidies or low-interest loans can incentivize villagers to construct permanent, "pucca" houses, offering improved safety and security.

Empowering the Stewards of the Land: Farmers are the backbone of rural life. Implementing financial assistance programs, including subsidies or loans, encourages the adoption of soil conservation techniques and sustainable agricultural practices. This not only safeguards the precious land but also empowers farmers with the tools to increase yields and potentially diversify their income streams, fostering long-term agricultural resilience. By embracing these solutions and collaborating with the community, we can transform these challenges into opportunities, paving the way for a brighter and more prosperous future for the village.

CONCLUSION

As the curtain closes on this fascinating journey through the villages of Dima Hasao, a rich mosaic of inequality and diversity is revealed. The comparison research has revealed a wealth of priceless insights that illuminate the particular difficulties and situations that embellish each community's lived experiences. Amidst this variegated landscape, a similar thread runs across the narrative — a great regard for environmental preservation. With their guarded presence and struggles with the complexities of resource management, these settlements serve as a stark reminder of how urgent it is to develop sustainable practices and raise awareness of conservation. The fragile balance that unites these communities may be preserved by fostering a shared commitment to environmental well-being, strengthening their resistance to the looming dangers of climate change.

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PLASTIC'S FULL LIFE CYCLE: ASSESSING PRODUCTION, WASTE, AND AIR QUALITY IMPACTS ON CLIMATE

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ABSTRACT

India stances at the convergencence of rapid economic growth, insightful of environmental challenges, and aspiring climate goals. The nation's association with plastic is a miniature of this complicated dynamic. While providing economic and practical benefit, plastic pollution has aroused as a critical environmental threat. This article discusses about the plastic crisis in India which is naturally and fundamentally associated to the climate crisis. The interrelation leads to manifesting across its whole lifecycle i.e., from fossil fuel extraction then production to consumption and its disposal. The linear "take-make-dispose" model of plastic economy generates significant greenhouse gas (GHG) emissions at every stage which adds to toxic air pollution through familiar waste management practices like open burning, and perpetuates a cycle of environmental and public health harm. By studying each phase of the lifecycle based on Indian viewpoint, this article highlights the localized impacts, mainly on-air quality and climate vulnerability. Furthermore, it evaluates India's existing policy framework which includes the Extended Producer Responsibility (EPR) guidelines and the ambitious ban on select single-use plastics, identifying their gaps and its opportunities. Finally, the article suggests a strategic change towards a circular economy as an essential pathway for India. This will simultaneously mitigate climate change, reduce air pollution, and manage plastic waste in the area. This will also provide help to align its national development objectives along with international climate commitments.

Key words: Plastic waste lifecycle, waste management, air pollution, greenhouse gas emissions, climate change, circular economy, sustainable development.

THE DUAL CHALLENGE OF PLASTIC AND CLIMATE CHANGE

Globally, India is the third-largest generator of plastic waste which annually produce approximately 3.5 million metric tonnes by Central Pollution Control Board (CPCB, 2019). Its huge population, rapidly increasing consumer economy and widespread use of wrapping/packaging have created a waste management crisis of monumental proportions. At the same time, India is on the front lines of climate change, facing increasing dangers from extreme heat waves, erratic monsoons, rising sea levels, and glacial melt. The linkage between these crises, however, remains under-examined in mainstream discourse. The common thread weaving plastic pollution and climate change together is fossil fuels. Over 99% of plastic waste is generated from chemicals which is obtained from fossil fuels, with the sector consuming an approximately 6% of global oil production (World Economic Forum, 2016). Consequently, the lifecycle of plastic i.e., from its birth as a fossil fuel to its often poorly managed end-of-life is an important and rising source of greenhouse gas emissions. Moreover, country like India, which is both a major plastic consumer and a climate-vulnerable nation, understanding this link is not an academic exercise but a necessity for effective policy-making. This article will reconstruct the plastic lifecycle in the Indian context, by examining its contribution to climate change and its direct impact on air quality. It will explore how India's unique socio-economic fabric, particularly its massive informal waste sector, shapes the environmental outcomes of plastic disposal. The article will conclude by arguing that a transition to a circular economy for plastics is not just a waste management strategy but a critical climate mitigation and public health imperative.

THE LIFECYCLE ANALYSIS: EMISSIONS AT EVERY STAGE

The climatic impact of plastic is cumulative, accruing across its value chain. The following sections break down this lifecycle within India's specific context.

STAGE 1: FOSSIL FUEL EXTRACTION AND REFINING

The life of plastic starts with the extraction of oil and natural gas from deep underground or under the sea. India, even though a significant oil importer, has a substantial petrochemical industry. Various companies like Reliance Industries and Indian Oil Corporation work on massive refineries and crackers that produce polymer feed stocks like propylene and ethylene. The processes like extraction, transportation, and refining processes are highly energy-concentrated. The most common emissions during extraction and transport are fugitive emissions of methane which is a potent GHG with over 80 times the warming power of CO_2 over 20 years (Zheng and Suh, 2019). The refining process itself involves the burning of fossil fuels for power, then releasing CO_2 and air pollutants like nitrogen oxides (NOx) and sulfuroxides (SOx).The expansion of India's petrochemical sector to meet plastic demand directly contradicts its climate goals under the Paris Agreement. The energy required for these processes often comes from coal-fired power grids, further increasing the carbon footprint of virgin plastic produced in India.

STAGE 2: PRODUCTION AND MANUFACTURING

The second step is to break down the processed hydrocarbons into monomers, which are, in turn, then polymerized into plastics. This is then further compounded by producing items and objects where much of the energy and resources involved are used in the heating and forming of materials. The cooking process is very energy-intensive, as it involves breaking (cracking) molecules by the application of very high heat often derived from the burning of fossil fuels which generates the necessary temperature. In addition, the production of plastic products is electricity dependent, which in India is mainly coal based (approximately 72% of generation) according to the International Energy Agency (IEA, 2021). That's a double carbon burden. In addition to GHGs, these plants are point sources of toxic air pollutants such as VOCs that form ground-level ozone and can threaten nearby communities.

STAGE 3: THE ILLUSION OF USE AND THE RISE OF MICROPLASTICS

The third stage of plastic products is often mistakenly considered low-impact. For most of the single-use items, this phase is fleeting. However, for some applications and their emissions during use can be of some importance.

Consumption and Transportation: The use of some products can also create emissions. The trucking of bottled water and goods around India's vast landscape using diesel trucks, for example, leads to significant CO2 emissions. The emissions impact of this stage is generally smaller than those above, but the 'locked in' carbon in single-use products, used briefly yet lasting for many generations, is the inefficient use of one of the universe's most precious resources.

Microplastics and the Carbon Cycle: An imminent concern is the role of microplastics in terrestrial and marine ecosystems. As plastic waste break down into fragments of micro- and nanoplastics which contaminates every part of the world. According to some recent research, this plastic pollution may be interfering with the planet's natural active carbon sink by absorbing about 25% of anthropogenic CO_2 emission. Phytoplankton plays a very important role in this biological carbon pump. Early studies suggests that microplastics can hinder phytoplankton growth and photosynthesis, which may potentially lower the ocean's capacity to absorb carbon (Shen *et al.,* 2020). While this research is still in early stages but it highlights the potentially harmful feedback loop where plastic pollution damages the natural system that help to reduce the climate change.

STAGE 4: END-OF-LIFE: WHERE THE CRISIS CONVERGES

Nowhere in the end of its life in Indian plastic poses direct and visible threat to both the climate and air quality. India's formal waste management system, includes both collection and recycling, is saturated, with over-reliance on a large sector of informal waste pickers and a prevalence of unacceptable disposal methods.

Land filling: The majority of India's plastic waste, 90 percent, finds its way into dumpsites and not engineered landfills. When such organic matter comes into contact with plastic waste in an anaerobic environment, methane is produced. Although some landfills harvest this gas, the majority of open dumps, including the notorious Ghazipur in Delhi, emit methane constantly into the atmosphere (Narayan and Visvanathan, 2018).

Recycling: Recycling is considered a solution to the proliferation of single-use plastic, but in India, the reality is quite complicated. Most of the recycling is done in the informal sector, where it is economically essential for millions but in many cases inefficient and dangerous. Procedures like washing and melting plastic are performed in tiny, unregulated factories without pollution controls. And, critically, the process of breaking down bottle waste (including one of Coca-Cola's biggest bottles) and recycling it into other bottles or non-recyclable jackets, like above, is also down cycling that is, the only downward slope toward its eventual (and inevitable) demise into the environment to a dump or incinerator.

Open Burning: The link between Air Pollution and Climate Change: This is the most detrimental end-of-life pathway in the Indian context. Due to a shortage of systematic collection, non-recyclable and low-value plastic is often burned in open piles. When plastic waste is burned in open, as a most common practice to reduce waste volume in landfills or at dump sites which does not combust efficiently. This incomplete combustion of waste releases a host of pollutants.

Black Carbon (Soot): This is a primary source of black carbon (BC), a key component of particulate matter (PM2.5). Black carbon is a powerful climate forcer with a global warming potential of hundreds times that of CO2 over a short period of time. When it lands on ice and snow, it lowers reflectivity (albedo), which speeds up melting. This is a serious issue for the Himalayan glaciers that nourish India's main rivers.

Carbon Dioxide (CO2): This released from the fossil carbon entrenched in the plastic waste.

Methane (CH4): This can be released from smoldering fires, forest fires.

Toxic Air Pollutants: It mainly includes dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs), which are generally known for its carcinogens nature and causes respiratory and cardiovascular diseases.

A study by (Pandey *et al.,* 2021) approximately 22,000 tonnes of PM2.5 emitted annually, along with significant amounts of BC and other toxins in the open waste burning across India. This mainly contributes to the northern Indian air pollution crisis, especially during winter season when atmospheric conditions trap pollutants close to the ground. This significantly worsens air quality, which is already at crisis levels in many Indian cities, and leads to respiratory illnesses, cancers, and other health issues (Garcia-Käufer *et al.,* 2021).

Incineration (Waste-to-Energy): Incineration plants are often promoted as a best way to lessen waste landfill burden and produce energy. However, these plants are highly controversial. Burning mixed plastic waste emits fossil CO_2. If the waste stream includes PVC which is very common in pipes and packaging and it releases dioxins. Although modern plants have pollution control devices, their operational inefficiencies and the high moisture content of Indian waste. This requires extra fuel which can make them net carbon emitters and sources of toxic air pollution (Sharma and Chandel, 2021).These plants are often located near marginalized communities, exposing them to greater health risks.

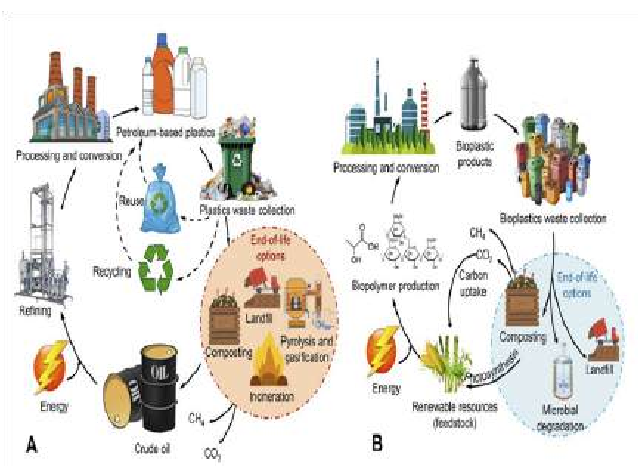

Fig. 1: Life cycle assessment of fossil-based plastic (A) and bioplastic (B) showing the production, end-of-life options, and environmental impacts (Source: Jiao et al., 2024)

THE AIR QUALITY AND PUBLIC HEALTH IMPERATIVE

The atmospheric emissions from the plastic lifecycle contribute to a serious public health crisis. India is home to 39 of the world's 50 most polluted cities (IQ Air, 2023). PM2.5releasedfrom open waste burning, along with emissions from industry, vehicles, and agriculture, creates a toxic haze that forms blankets over large areas. The direct exposure to PM2.5 is linked to Respirable diseases like asthma, bronchitis, lung cancer, heart attacks, and strokes. The harmful additives released from burning plastic, like dioxins which are bio accumulative and can disrupt endocrine system and immune systems of the body. The health impacts on body are immense. The State of Global Air report (2020) estimated that air pollution was the main cause for the deaths over 1.6 million in India during 2019. While not all of these deaths are attributable to plastic burning but it is a major and one of the growing factors, especially affecting the most of the waste pickers, informal recyclers, and communities settled near dumping grounds and industrial cluster areas.

Plastic Waste Management Rules (2016, amended 2021 & 2022): These rules form the foundation stone of India's policy on plastic waste. The 2022 amendment of rules strengthened the guidelines for Extended Producer Responsibility (EPR). These rules make the brands physically and financially responsible for managing the plastic waste which they introduce to the market.EPR has the capability to create a formal, structured waste collection system and incentivize producers to redesign packaging for recyclability. The current EPR framework focuses strongly on recycling plastic waste and end-of-life management, giving insufficient attention to the supreme need for the source reduction. It also risks legitimizing incineration and co-processing in cement kilns as acceptable EPR activities, spreading GHG and toxic emissions.

Ban on Single-Use Plastics (2022): India banned on 19 categories which includes single-use plastic items. This is a daring step towards the reduction of single-use plastic items source. The success of this ban leads to a turning point on the enforcement at the state and municipal levels and the availability of reasonably priced and provide another scalable possibility. The climate benefit of alternatives (for e.g., cotton bags, which have a high-water footprint, or biodegradable plastics, which require specific composting conditions) must be carefully evaluated to avoid any accidental consequences.

National Climate Policies: India Nationally Determined Contributions (NDCs) under Paris Agreement are mostly cantered on Renewable Energy, Energy Efficiency, and Green Hydrogen. Its plastic lifecycle, as one of the major sources of emissions, is still a blind spot in its formal climate strategy. The inclusion of plastic production, reduction and sustainable waste management in future NDCs is the next necessary step.

THE POLICY LANDSCAPE: GAPS AND OPPORTUNITIES

India has a developed policy framework to deal with plastic pollution, but its efficiency in mitigating climate impact is varied.

TECHNOLOGICAL AND SOCIAL INNOVATION

Alternative Materials: by promoting real alternatives like compostable bio plastics for certain uses where industrial composting facilities exist. Also bring back traditional materials like jute, cloth and paper. Lifecycle assessments must guide this shift to make sure these alternatives actually have a lower environmental impact.

Advanced Recycling: by exploring chemical recycling technologies that can break down bigger plastics into their molecular level. Even though these plastics must be critically evaluated for their energy use and emissions to ensure they are an improvement over new production.

Waste-to-Energy (WtE): While incinerating waste in controlled WtE plants can reduce waste volume and Produce energy, it is a controversial solution. It relies on high-calorific waste, sophisticated and advanced pollution control equipments. This can also discourage waste reduction and recycling process. In Indian, waste is in large quantity, mostly wet with low-calorific importance, WtE plants mostly face struggle and easily become a source of pollution if not properly managed.

BEHAVIORAL CHANGE AND CONSUMER RESPONSIBILITY

In India, plastic pollution is a serious environmental crisis, worsen by rapid urbanization and a dependence on single-use plastics. While government policies like the Plastic Waste Management Rules are very important, ground solutions depend on major changes in behavioral change and the willingness of consumer to take responsibility. Behavioral change means shifting one's mindset from convenience to awareness. This mainly involves public awareness campaigns which should highlighting the severe impacts of plastic pollution such as clogged drains causing floods, dangers to wildlife, and microplastic contamination. Educational initiatives programs must reach to all demographic's groups, encouraging the use of reusable bags, bottles, and containers. Reviving this traditional practice of bringing one's own bag for shopping needs a strong revival. However, just awareness alone is not sufficient. Consumers need to take their responsibility seriously. This means refusing unnecessary plastic packaging, selecting sustainable options, and properly sorting waste at home to ensure plastic is recycled instead of end up in landfills or waterways. The effectiveness of any government ban totally depends on their citizen comply and their collective refusal to accept plastic as a normal part of daily life. Ultimately, by tackling plastic pollution in India requires a combined approach. Government rules and regulation provides the framework, corporate innovation offers alternatives, but it's the millions of choices made by consumers that will bring about the real change on-ground for a cleaner future. The responsibility to refuse, reduce, and reuse lies with the public.

THE WAY FORWARD: 'A CIRCULAR ECONOMY AS CLIMATE ACTION'

The plastic-climate challenge demands a structural change from the linear to a circular economy. This is achieved through certain key pillars:

Reduce: The most effective climate lever for the plastics industry is not to recycle more, but to make less. This demands for the enforcement of the SUP ban, support for reusable packaging systems (e.g. refillable containers) and consumer awareness. Policy should incentivize innovation in different approaches to delivery, not just in alternative content.

Reimagine: the products must be designed for its durability, to be reused and to be easily recycled. Eliminating multi-layered packaging (which is unrecyclable) and toxic additives is crucial. The EPR framework should be refined to incentivise producers for light weighting and designing for circularity.

Formalize and empower: on the basis of layman's perspective, the informal waste sector is the informal backbone of Indian recycling system. Policies must integrate and formalize these workers, securing fair wages, safe working conditions and social security. This enhances recycling efficiency and minimizes the environmental health risks or hazards associated with the informal processing.

Manage End-of-Life Responsibility: Invest in modern, effective, and transparent material recovery facilities and composting facilities of plants to divert waste from dumps and incinerators. Phase out open burning and ensure that any thermal treatment operates according to the strictest emission standards requirements and only treats non-recyclable waste.

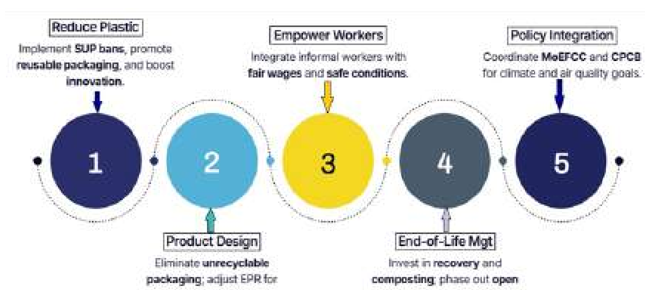

Fig. 2: Key pillars for systemic plastic waste management and climate mitigation

Integrate Policies: The mandates of the Ministry of Environment, Forest and Climate Change (MoEFCC) and the

CPCB must interlink plastic waste management with climate mitigation and air quality goals or objectives. The National Clean Air Programme (NCAP) must also explicitly identify open waste burning as a key source for targeted action.

CONCLUSION

The story of plastic waste in India is more than a tale of littered/tormented sceneries with blocked oceans. It is a story deeply engraved in fossil fuels and written in the language of greenhouse gas emissions and toxic smoke. The plastic lifecycle is a considerable, yet often overlooked, driver of climate change and air pollution, burdening the country's development and public health. By tackling this dual challenge requires moving beyond siloed solutions. A piecemeal approach that focuses only on cleaning up waste without stopping the tap of virgin plastic production, or one that promotes end-of-life incineration over reduction, is fundamentally inadequate. True solutions of the plastic waste lie in a holistic and circular economy framework. This mainly recognizes the intrinsic linkage between production, consumption, and disposal. For India to meet its developmental goals and its climatic responsibilities, breaking free from the linear plastic economy is not an environmental option but it is an economic and morally important. The path will lead to a cleaner and cooler air India which leads to confronting the plastic lifecycle face to face.

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CULTIVATING RESILIENCE: INTEGRATING TRADITIONAL KNOWLEDGE AND AGRO-ECOTOURISM FOR SOCIO-ECOLOGICAL REVITALIZATION IN UTTARAKHAND, INDIA

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ABSTRACT

The Himalayan state of Uttarakhand stands at a critical juncture, where its profound cultural heritage and ecological wealth are increasingly threatened by climate change, out-migration, and the declining viability of traditional agriculture. This socio-ecological crisis jeopardizes the resilience of its mountain communities and the conservation of native biodiversity. The present work posits that agro-ecotourism which is an integrated approach blending sustainable agriculture, ecological stewardship, and responsible tourism presents a transformative pathway toward sustainable development of the region. The study focuses on the synergy of the coupled dimension of agri-ecological model which can diversify local livelihoods, create much-needed non-farm employment, and enhance farm incomes through the direct marketing of organic produce. Consequently, it provides a tangible economic incentive to preserve indigenous agricultural practices, heirloom seed varieties, and traditional knowledge, which are often abandoned. Furthermore, by valuing the community's role as custodians of the landscape, agro-ecotourism can foster grassroots-led conservation efforts, strengthening the management of forests and water resources. The study contends that for Uttarakhand, agro-ecotourism is not merely a niche market but a vital strategy for revitalizing rural economies, curbing migration, and safeguarding its unique socio-ecological fabric.

Key words: Agro-ecotourism, biodiversity conservation, community involvement, ecosystem services, socio-ecological balance.

COUPLED INTERACTIONS OF AGRICULTURE, ECOLOGY AND HUMAN EXPERIENCE

The Himalayan region, characterized by its ecological fragility and rich cultural heritage, faces significant challenges from climate change, economic marginalization, and out-migration. In this context, agro-ecotourism has emerged as a promising integrated strategy to foster sustainable development. This model represents a synergistic blend of sustainable agriculture, ecological stewardship, and responsible tourism, creating a virtuous cycle that benefits both the environment and local communities. At its core, agro-ecotourism transforms conventional agricultural landscapes into dynamic, multifunctional spaces. Farms cease to be merely sites of food production and become living classrooms and experiential retreats. This allows urban visitors to escape the homogenized urban environment and immerse themselves in the serene rhythms of rural life. Tourist activities are designed to be participatory and educational, including plucking tea leaves, learning about composting techniques, sowing seeds in traditional terrace farms, harvesting indigenous crops, and tasting locally prepared traditional foods and herbal teas. This direct engagement fosters a deep, personal connection with nature and a genuine appreciation for rural wisdom and ecological heritage, making the tourist experience both transformative and educational.

The socio-economic impacts of this model are profound. For local communities, agro-ecotourism provides a crucial mechanism for livelihood diversification and economic resilience. It moves beyond subsistence farming by generating supplementary income streams for farmers, who are empowered to showcase their knowledge and ecological practices. Furthermore, it creates new employment opportunities in allied sectors such as home stay management, tour guiding, local handicrafts, and value-added food processing. This economic diversification is particularly significant for rural youth and women, offering viable and dignified local alternatives to precarious urban migration. By creating attractive local enterprises, agro-ecotourism can help curb distress migration and even encourage reverse migration, thereby revitalizing the social fabric of mountain villages and strengthening community bonds. Ecologically, the agro-ecotourism model is intrinsically aligned with the principles of conservation and sustainability, as highlighted by Kumar *et al.,* (2021). The presence of eco-conscious tourists and the market premium placed on organic, local produce provide a powerful economic incentive for farmers to adopt and maintain ecological farming practices. This includes soil and water conservation techniques, the preservation of native seed varieties, and the enhancement of on-farm biodiversity. The model, therefore, creates a tangible link between a healthy ecosystem and a thriving local economy, encouraging community-led initiatives for forest and water resource management (Rawal & Pant, 2024).In conclusion, agro-ecotourism represents a sustainable and holistic pathway for community development in the Himalayas. It creates a powerful win-win scenario by enriching the visitor's experience through authentic cultural immersion and natural serenity, while simultaneously empowering host communities economically and revitalizing their ecological and cultural heritage. By integrating farming, tourism, and local enterprise into a single, resilient model, agro-ecotourism stands as a vital strategy for building socio-ecological resilience in the face of global change.

RESTORING NATIVE BIODIVERSITY THROUGH TRADITIONAL KNOWLEDGE: AN INTEGRATED APPROACH FOR UTTARAKHAND'S SUSTAINABLE DEVELOPMENT

The Uttarakhand Himalaya represents a vital repository of traditional ecological knowledge (TEK) and traditional knowledge-based systems (TKBS), embodying centuries of accumulated wisdom regarding sustainable resource management and biodiversity conservation. As documented by Negi (2010), this knowledge system encompasses sophisticated understanding of native species ecology, particularly concerning the sustainable utilization of Non-Wood Forest Products (NWFPs) such as Zanthoxylum armatum DC. (Timur), Myrica esculenta Buch-Ham. (Kafal), and Valeriana jatamansi Jones. (Tagar) etc. These species represent not merely biological resources but integral components of cultural heritage and traditional healthcare systems, forming the foundation of local communities' relationship with their environment.

The current ecological challenges facing Uttarakhand, including biodiversity loss, habitat fragmentation, and climate change impacts, necessitate innovative approaches that blend traditional wisdom with contemporary conservation science. Integrating native NWFP species into agroforestry-based ecotourism models presents a promising strategy for enhancing both ecological resilience and socioeconomic viability. This integration creates synergistic benefits where agricultural landscapes transform into multifunctional systems supporting biodiversity conservation while generating sustainable livelihoods. The incorporation of species like Timur, Kafal, and Tagar into farming systems not only preserves genetic diversity but also enhances ecosystem stability through the maintenance of native floral compositions and will form a part of ecosystem-based adaptations. Community-run nurseries emerge as crucial institutions in this integrated framework, serving dual purposes of biodiversity conservation and economic empowerment. These nurseries facilitate the propagation of native species while ensuring genetic purity and ecological adaptation. Furthermore, they strengthen forest-farm linkages, creating ecological corridors that support wildlife movement and gene flow. The commercial potential of these species can be realized through ethical and sustainable value chains, where community ownership and benefit-sharing mechanisms ensure equitable distribution of economic gains while maintaining ecological sustainability.

The concept of "ethnobotanical trails" within agro-ecotourism farms offers an innovative platform for knowledge exchange and cultural preservation. These curated experiential pathways enable visitors to engage with the rich tapestry of traditional plant knowledge, understanding medicinal applications, culinary uses, and cultural significance of native species. Each trail becomes a living classroom where traditional knowledge holders can demonstrate sustainable harvesting techniques, seasonal management practices, and conservation ethics. This interactive learning experience not only enhances visitor engagement but also reinforces the economic value of preserved traditional knowledge, creating incentives for intergenerational knowledge transfer.

The ecological benefits of integrating native species extend beyond biodiversity conservation. Systems incorporating NWFPs demonstrate enhanced ecosystem functionality through improved pollination services, soil stabilization, and carbon sequestration capacities. The deep root systems of native trees prevent soil erosion on mountain slopes, while their diverse phenology supports pollinator populations throughout the year. Additionally, these mixed-species systems contribute significantly to carbon storage both in biomass and soil organic matter, aligning with global climate change mitigation efforts while maintaining local ecological integrity.

The success of this integrated approach depends critically on community participation and institutional support. Local communities serve as both knowledge holders and implementation partners, ensuring that conservation strategies align with cultural values and practical realities.

Community-led monitoring systems can track ecological indicators while maintaining traditional management practices. Furthermore, the development of geographic indication tags and certification schemes for NWFP products can enhance market value while ensuring sustainable harvesting protocols.

In conclusion, the restoration of native biodiversity through traditional knowledge represents a holistic approach to sustainable development in the Uttarakhand Himalaya. By integrating TEK with modern conservation approaches through agro-ecotourism frameworks, this model achieves simultaneous progress toward ecological sustainability, cultural preservation, and economic resilience. The continued documentation, validation, and application of traditional knowledge, combined with supportive policies and market linkages, can transform Uttarakhand's biological and cultural heritage into foundations for sustainable development, creating a replicable model for other mountain regions facing similar challenges.

SYNERGIZING AGRICULTURE AND TOURISM: A MULTI-MODEL AGENDA FOR SUSTAINABLE DEVELOPMENT IN UTTARAKHAND

While the Kausani Tea Estates remain flagship examples offering immersive tea tourism experiences including plantation trails, eco-certification programs, and women-led processing units other innovative models across the Uttarakhand Himalaya demonstrate the remarkable versatility and adaptability of agro-ecotourism. These diverse initiatives illustrate how the fundamental principles of integrating agriculture, ecology, and tourism can be successfully applied across different ecological zones and cultural contexts, creating unique and sustainable livelihood opportunities beyond conventional tea tourism.

In the temperate fruit-growing regions, particularly around Ramgarh (Nainital) and Chaubatia (Ranikhet), horticulture-based agro-ecotourism has flourished. Here, visitors can participate in apple and peach orchards, learning about integrated pest management and organic cultivation practices while enjoying "blossom tourism" during spring. These farms often incorporate apiculture, demonstrating the crucial link between fruit cultivation and pollinator conservation, while also producing and selling value-added products like artisanal jams, preserves, and honey. This model not only diversifies farm income but also extends the tourism season beyond traditional months.

The mid-elevation zones have seen the emergence of spice-centric agro-ecotourism, where farms cultivate traditional spices such as turmeric, ginger, and coriander using organic methods. These initiatives often include participatory workshops where visitors learn about spice processing, traditional medicinal applications, and culinary uses. The establishment of community-owned spice processing units has enabled farmers to capture greater value from their produce while providing authentic, hands-on experiences for tourists interested in local cuisine and traditional health practices.

In higher altitude areas, particularly those facing agricultural abandonment, medicinal plant conservation initiatives have creatively integrated tourism components. Communities have established "conservation gardens" for threatened medicinal species like *Picrorhizakurrooa* Royle. (Kutki) and *Aconitum heterophyllum* Wall. (Atis), where visitors learn about sustainable harvesting techniques and traditional healing knowledge. These projects often collaborate with research institutions to document and validate traditional knowledge while ensuring that tourism activities directly support conservation objectives.

The integration of livestock-based enterprises represents another innovative dimension. Several villages have developed experiences around traditional dairy practices, including hands-on sessions in making artisanal cheeses and local sweets. These initiatives often highlight the importance of indigenous cattle breeds and sustainable grazing practices, demonstrating the role of livestock in maintaining mountain ecosystems while providing supplementary income through tourism.

Community-managed forest initiatives have also embraced agro-ecotourism by developing "conservation trails" that showcase sustainable harvesting of NTFPs (Non Timber forest Products). These experiences educate visitors about forest ecology, traditional resource management systems like Van Panchayats, and the cultural significance of various forest species. The revenue generated supports community conservation efforts while creating economic incentives for protecting forest ecosystems. What unites these diverse models is their foundation in local ecological knowledge, their emphasis on community participation, and their ability to create multiple revenue streams while promoting environmental conservation. Women's self-help groups often play a crucial role in these initiatives, managing homestays, food experiences, and handicraft demonstrations, thereby ensuring broader social benefits and gender empowerment.

The success of these varied agro-ecotourism models explained in Table 1 highlights the importance of context-specific approaches that build on local strengths and ecological conditions. Rather than replicating single templates, Uttarakhand's experience demonstrates the value of developing diverse tourism products that reflect the unique agricultural and cultural heritage of different micro-regions. This diversified approach, rooted in Ecosystem-based Adaptation (EbA) principles, not only spreads tourism benefits more widely but also creates a richer, more varied tourism landscape that can attract different visitor interests throughout the year. As Uttarakhand continues to develop its agro-ecotourism portfolio, the challenge lies in maintaining ecological integrity and community ownership while scaling up these initiatives. The state's experience offers valuable insights for other mountain regions seeking to develop sustainable tourism models that celebrate agricultural diversity, empower local communities, and conserve fragile ecosystems in the face of changing climatic and economic conditions.

Table 1: Agro-ecotourism strategies and examples in the Uttarakhand Himalaya

Model for Strategic Approach	Geographic Implementation	Core Synergistic Activities	Integrated livelihood and ecological benefits
Premium Plantation Tourism	Kausani (Bageshwar) Champawat	•Immersive tea trails; participatory plucking; •Ecosystem based Adaptation (EbA) practices like moisture-conserving shade trees and soil erosion control through contour planting demonstrated as part of the tour.	•Value-chain capture via direct sales; •Economic empowerment through women-led cooperatives; •Enhanced microclimate regulation and soil conservation.
Bio-Cultural Heritage Tourism	Almora, Bageshwar	•Ethnobotanical walks in community-conserved forests; •Workshops on cultivating climate-resilient native species as an EbA strategy for food and economic security.	•Premium markets for value-added herbal products; •Revitalization of TEK; •Conservation of genetic diversity and robust native species adapted to climate change.
Circular Economy Demonstrations	Pithoragarh, Nainital	•Interactive tours of integrated organic farms; hands-on composting/vermiculture; •Demonstrating EbA via water harvesting for irrigation and organic matter for soil health, building farm resilience.	•Diversified and resilient farm income; •Reduced input costs; improved soil water retention and carbon sequestration, •Mitigating climate impacts.
Agro-Cultural Festival Tourism	Kumaon–Garhwal Belt (Across Districts)	•Farm visits linked to festivals (Harela, Phooldeyi); •Participatory seed sowing of native varieties; •EbA messaging integrated into rituals to promote community-led conservation.	•Year-round tourism demand; •Intergenerational transmission of climate-resilient practices; •Enhanced community cohesion for managing communal natural resources.
Community-Led Ecotourism	Mukteshwar (Nainital), Munsiyari (Pithoragarh)	•Homestay networks and guided trails highlighting community-based forest management (Van Panchayats) as a core EbA approach for disaster risk reduction and water security.	•Direct revenue retention within the community; •Viable alternatives to out-migration; •Incentivized protection of watersheds and biodiversity corridors.
Aqua-Agro Ecotourism	Bhimtal (Nainital), Tehri, Tons Valley (Dehradun)	•Educational tours of integrated aquaculture and watershed management; •Demonstrating EbA techniques like farm ponds for irrigation and check dams for groundwater recharge as climate adaptation.	•Additional income from fish and tourism; •Improved water security and drought resilience; •Reduced soil erosion and landslide risk through water management.

These diverse initiatives unfolding across Uttarakhand demonstrate conclusively that agro-ecotourism's potential extends far beyond the confines of commercial tea estates. It emerges not as a singular activity, but as a holistic and synergistic approach that deliberately weaves together the threads of sustainable agriculture, forest conservation, and rich cultural heritage. By design, this approach transforms the rural landscape into a multifunctional space that simultaneously produces food, conserves biodiversity, generates dignified employment, and educates visitors. Ultimately, it is this very integration this creation of a resilient, interlinked system that forges sustainable and climate-resilient livelihoods, securing a viable future for Uttarakhand's mountain communities in harmony with their priceless environment.

CULTURAL ECOLOGY, GANDHIAN ETHOS, AND SUSTAINABLE DEVELOPMENT GOALS (SDGS): A HOLISTIC VISION FOR AGRO-ECOTOURISM

The transformative potential of agro-ecotourism in Uttarakhand extends beyond economic diversification, finding its deepest roots in the region's rich cultural ecology and philosophical heritage. This integrated approach weaves together traditional wisdom, ethical principles, and modern sustainability goals to create a truly holistic model for regional development. The cultural landscape of Uttarakhand provides a living tapestry of eco-conscious traditions (Figure 1 and 2), where festivals like Harela and Phooldeyiare not merely seasonal celebrations but profound expressions of environmental stewardship (Bhatt *et al.,*2024). These festivals, with their rituals of collective sowing, floral offerings, and forest worship, represent centuries-old practices of sustainable coexistence with nature. When integrated into agro-tourism circuits, they offer visitors immersive experiences that transcend conventional tourism, providing deep insight into the ecological wisdom embedded in local culture.

Depicting the role of nature in Ancient practices & timeless ecological wisdom

Fig.1. Kausani tea trails

Fig.2. Anashakti Ashram

This cultural foundation finds philosophical reinforcement in the Gandhian ethos prevalent in the region, particularly through landmarks like the Anashaktiashram in Kausani. The principles of self-reliance (Swaraj), simplicity, and peace that Gandhi championed during his stay here provide a spiritual and ethical dimension to sustainable tourism development. These values align perfectly with the concept of localized, community-controlled tourism that minimizes ecological footprint while maximizing local benefit. The Gandhian emphasis on village self-sufficiency and appropriate technology informs a tourism model that prioritizes community well-being over mass commercialization, creating a meaningful alternative to conventional tourism paradigms.

The convergence of cultural ecology and Gandhian philosophy with modern sustainability frameworks finds concrete expression through the SDGs. Agro-ecotourism serves as a practical vehicle for achieving multiple SDGs simultaneously through its various components. Organic farming practices and agricultural residue recycling directly contribute to SDG 13 (Climate Action) through enhanced carbon sequestration and to SDG 15 (Life on Land) by improving soil health and reducing chemical pollution. The integration of native Non-Wood Forest Products (NWFPs) into farming systems supports biodiversity conservation, further advancing SDG 15 while creating sustainable economic opportunities (Bhatt& Jugran Pant (2024). The social dimensions of agro-ecotourism powerfully address key developmental targets. Women-led initiatives in processing units and homestays directly advance SDG 5 (Gender Equality) by enhancing women's income, decision-making power, and social standing. Community-based forest tourism models strengthen SDG 11 (Sustainable Cities and Communities) and SDG 16 (Peace, Justice and Strong Institutions) by reinforcing local governance systems like Van Panchayats and fostering participatory conservation. Educational components, including farm learning centers and watershed tourism, support SDG 4 (Quality Education) by building environmental awareness and practical skills, while sustainable water management practices contribute to SDG 6 (Clean Water and Sanitation).

This multi-dimensional approach demonstrates that agro-ecotourism in Uttarakhand represents more than an economic strategy it is a comprehensive approach to sustainable development that harmonizes cultural preservation, ethical principles, and ecological conservation. By integrating traditional ecological knowledge with Gandhian values and aligning them with global sustainability targets, Uttarakhand is pioneering a development model that offers viable livelihoods while strengthening environmental resilience and cultural identity. This integrated approach provides a replicable framework for other mountain regions seeking to balance conservation with community well-being, demonstrating that true sustainability emerges from the synergistic relationship between cultural heritage, ethical values, and ecological stewardship.

NAVIGATING CHALLENGES TOWARD SUSTAINABLE AGRO-ECOTOURISM

The development of agro-ecotourism in Uttarakhand faces significant challenges that threaten its long-term viability. Key issues include unregulated tourism leading to waste accumulation and forest degradation, heightened human-wildlife conflicts, seasonal outmigration that reduces labor availability, and limited infrastructure and marketing support for local products. These interconnected problems risk undermining the very ecological and social foundations that make agro-ecotourism attractive. To ensure ecological responsibility and social inclusivity, a multi-pronged sustainability strategy is essential. This includes strengthening participatory governance through Van Panchayats to regulate tourism impacts and conserve forests. Implementing eco-certification for local products like tea can enhance market value while ensuring environmental credibility. Concurrently, capacity building for community-based eco-hospitality and entrepreneurship is crucial for developing local skills. The strategic integration of cultural festivals and TEK into tourism narratives will promote cultural continuity, while developing community-owned "Tea Trails" and homestays ensures equitable benefit-sharing. These coordinated measures can transform challenges into opportunities, creating a self-reinforcing system where tourism growth directly supports environmental conservation, cultural preservation, and local economic resilience. By embedding these practices, Uttarakhand can pioneer a genuinely sustainable agro-ecotourism model that benefits both communities and ecosystems for generations to come.

CONCLUSION

Agro-ecotourism in the Uttarakhand Himalaya transcends conventional tourism, emerging as a vital movement to revitalize mountain communities. It represents a profound reconnection between people and nature, aiming to revive the region's ecological soul. This innovative model merges sustainable agriculture with ecological stewardship and experiential education, creating a new paradigm of prosperity rooted in environmental sustainability.

By restoring native biodiversity, promoting organic farming, and empowering local communities especially women through homestays and cultural initiatives, agro-ecotourism significantly boosts socio-economic conditions. It positions Uttarakhand as a pioneer in demonstrating how mountain regions can achieve resilience and inclusivity. In the fragrance of fresh tea leaves, the whisper of ancient forests, and the songs of hill communities lies a powerful visiona harmonious balance between livelihoods and landscapes that truly celebrates the synergy of Nature, Knowledge, and Nurture for generations to come.

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MORPHOMETRIC PARAMETERS AND THEIR CORRELATION: A STUDY OF GLACIERS IN THE UPPER GORI GANGA BASIN, CENTRAL HIMALAYA

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ABSTRACT

This study analyses the morphometric parameters of nine glaciers located in the Upper Gori Ganga Basin of the Central Himalaya and explores their interconnections. By examining important glacier features such as Equilibrium Line Altitude (ELA), area, length, width, elevation, elongation quotient, relief ratio, and snout index, this paper seeks to identify patterns and relationships that determine the glacier morphology and their reactions to diverse topographical conditions within the same basin. The primary objective is to comprehend how these parameters interact, influence one another, and shape glacier morphology in this area, offering valuable insights into the variations in glacier morphological and morphometric trends and their implications for climate change.

Key words: Central Himalaya, Glacier, Equilibrium Line Altitude (ELA), Morphometry, GIS.

INTRODUCTION

Morphometric analysis refers quantitative assessment of the shape, form, and dimensions of the landforms. This includes measuring various physical features on Earth's surface, such as elevation, slope, area, and other geometric properties (Clarke, 1966; Pike *et. al.,* 2009; Horn & D'Oleire-Oltmanns, 2021). Such analysis is essential for classifying and examining different landforms, providing insights into their formation and evolution. Glacial morphometric parameters are quantitative measures used to describe glaciers' shape, size, and structure (Schiefer *et. al.,* 2008). The focus of glacial morphometry lies in measuring and analysing these physical characteristics (Ahmad et al., 2004). It provides a quantitative basis for spatial analysis, enhancing the use of Geographic Information Systems (GIS) and remote sensing techniques (Ali & Khan, 2013; Gudowicz & Paluszkiewicz, 2021). It is helpful to make out the impact of climate variation on glacial regions, sea-level rise, and other changing landscapes (Kopp *et. al.,* 2021).

Pandey *et. al.,* (2012) conducted a study on the glaciers of the Great Himalayan range, finding the correlation between different glacial morphometric parameters and changes in glacier area, as well as shifts in snout position. However, they have a limited impact on snout retreat or advancement. Liu *et. al.,* (2016) estimated the influence of morphometric parameters on glacial mass balance, reporting a significant correlation between glacier mass balance and mean altitude, while glacier size, aspect, and ice flow velocity were not statistically significant factors. Prasad and Naithani (2003) conducted a morphometric study on the Gangotri group of glaciers, revealing that slopes are steeper near the relatively narrow snout. According to King (1982), morphometric methods yield quantitative data that can be analysed through various statistical techniques to determine significance levels, allowing for an assessment of the likelihood of tested relationships. Examining glaciers' morphological features enhances understanding of their flow mechanisms and behaviour (Cuffey & Peterson, 2010). This paper attempts to explore the relationships between various calculated parameters.

MATERIAL AND METHODS

Satellite data, such as Landsat 8 and Google Earth satellite images, were used as the primary data source for delineating glacier boundaries and assessing glacier parameters. A high-resolution DEM (ALOS PALSAR 12.5 m) was used to derive topographic parameters including altitude, relief, and slope. To calculate glacial morphometry, the methodology proposed by Doornkamp & King (1971), Naithani *et. al.,* (2001), and Schiefer *et. al.,* (2008) has been used.

STUDY AREA

The Upper Gori Ganga River basin spans from 30°12'54" to 30°55'50" N latitude and from 79°59'37" to 80°17'23" E longitude, covering an area of 890.4 km² (Fig. 1). This basin hosts approximately 37 glaciers. The Milam glacier and its tributary glaciers are the most significant. The Milam glacier originates from the slopes of Hardeol (7151 m) and Trishuli East (7074 m) and extends in a southeast direction. Two cirques from the Trishuli and Hardeol Peaks, along with six subsidiary glaciers, feed the Milam Glacier. These subsidiary glaciers flow from the eastern rim of the Nanda Devi Sanctuary and include Surajkund (5.62 km), Dhulan (5.0 km), Mangroan (5.37 km), and Pacchmi Bamchu (6.86 km) as well as MUKG1 (Milam unknown glacier). On the eastern side, it is nourished by Billanlari glacier (2.55 km). Other notable glaciers in the region are Timphu, Pachu, Shalang, Burphu, Kalganga, Rata, Gonkha, and Bamlas.

The area comprises two geological zones i.e. the Higher Himalayan crystalline zone and the Tethyan sedimentary zone. Higher Himalayan zone includes Joshimath, Pandukeshwer, and Pindari formations. All studied glaciers lie north of the Trans Himadri Fault (THF) within the Tethys Himalayan segment, except Shalang glacier. The Tethys Himalaya includes Formations such as Rilkot, Burfu, Belju, Milam, and Ralam. The calc-phyllites and green siltstone from the Milam Formation are mainly found near the Milam glacier and close to Milam village. Reports indicate that within the glaciated region, this formation showcases graded and cross-bedding structures featuring medium to unsorted fine-grained arenaceous components (Dumka *et. al.,* 2013).

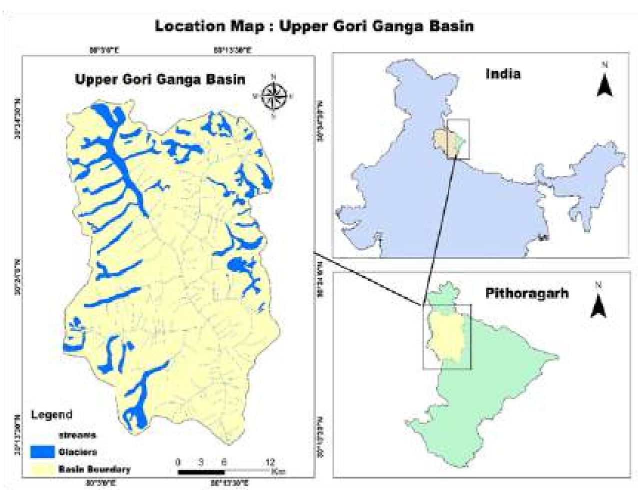

Fig. 1: Location map of the study area.

MORPHOMETRIC ANALYSIS

Morphometric parameters for the nine glaciers in the Upper Gori Ganga basin are measured and calculated (Table 1). A detailed description is presented below:

(i) Equilibrium line altitude (ELA)

It helps to estimate a glacier's mass balance. If the ELA splits the glacier into two equal sections, the mass is regarded as balanced. A larger accumulation zone indicates a positive mass, while a larger ablation zone results in a negative mass (Owen & Benn, 2005; Kulkarni, 1992). The ELA serves as an indicator of a glacier's sensitivity to temperature and precipitation changes (Zech *et. al.,* 2009).

For ELA calculation, the AAR (area accumulation ratio) method with AAR values of 0.45, 0.55, and 0.65 was applied (Meier & Post, 1962). Kulkarni (1992) noticed that glaciers covered with significant debris typically have a lower AAR (0.4) due to the insulation provided by the debris layer. The ELA related to the given AAR value was estimated using a linear interpolation formula (Reza, 2024)

Formula - $ELA = z + (Z - z)*(1 - AAR)$ (i)

$\text{Area Above ELA} = A*AAR$ (ii)

$\text{Area Below ELA} = A*(1 - AAR)$ (iii)

For Milam Glacier, the ELA is recorded at an altitude of 4845.4 meters above mean sea level (Masl). The following table (1) provides the altitudes of the ELA for selected 09 glaciers in the Upper Gori Ganga River basin.

Table 1: Illustration of ELA, Accumulation zone and Ablation Zone

Glaciers	z	Z	A	AAR 0.45	0.55	0.65	Acc. area (sq. km)	Abla-tion Area
Milam Glacier	3580	6392	35.82	5126.60	4845.40	4564.20	19.70	16.12
Shalang Glacier	3909	5787	11.30	4941.90	4754.10	4566.30	6.22	5.08
Burphu Glacier	3943	5801	6.90	4964.90	4779.10	4593.30	3.79	3.11
Kalganga Glacier	4093	5452	5.34	4840.45	4704.55	4568.65	2.94	2.40
Rata Glacier	4611	5863	3.96	5299.60	5174.40	5049.20	2.18	1.78
Gonkha Glacier	4772	5974	2.39	5433.10	5312.90	5192.70	1.31	1.07
Bamlas Glacier	4473	5834	5.77	5221.55	5085.45	4949.35	3.17	2.60
Pachu Glacier	3941	4694	4.08	4355.15	4279.85	4204.55	2.24	1.83
Timphu Glacier	4182	5672	3.90	5001.50	4852.50	4703.50	2.15	1.75

Fig. 2 represents that Milam Glacier has an ELA around 4845.4 m (AAR 0.55), which falls in the mid-range. The lowest ELA is observed for Pachu Glacier (4279.9 m), suggesting it exists in a colder microclimate or has favourable accumulation. Gonkha Glacier has the highest ELA (5312.9 m), indicating higher sensitivity to ablation or less snow accumulation. The trend across glaciers shows significant variability, which highlights the impact of localised topography and climate across the region.

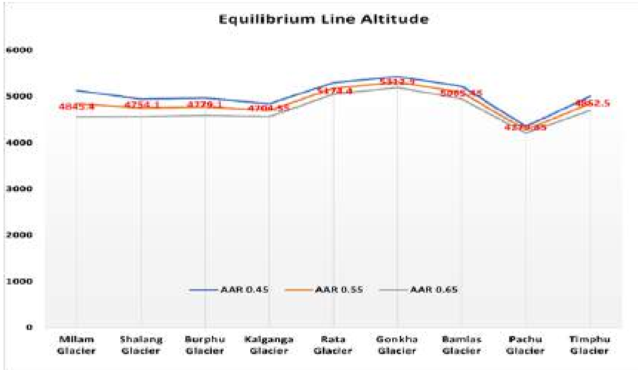

Fig. 2. Estimated ELA for the 09 Glaciers of Upper Gori Ganga Basin using AAR method.

(ii) Altitude of snout (z)

The glacier snout represents the terminus or lower extremity or end point of a glacier, where it meets its surrounding land or water body. It is the point at which the glacier loses its mass due to melting, calving, or sublimation. To determine the altitude of the glacier snout (the lowest point of the glacier terminus), the elevation value was extracted from the DEM of the snout as identified on Landsat 8 (Oct. 2023) satellite imagery. In Table 2, the altitude of the snout for the glaciers of the Upper Gori Ganga basin has been given.

(iii) Maximum Altitude (Z)

The altitude from the starting point of the zone of accumulation or the Bergschrund point is a maximum altitude of a glacier. The highest elevation point on the glacier surface was identified from the DEM. This is the highest point of the accumulation zone or the summit of the mountain from which the glacier originates. In Table 2, the maximum altitude for the 09 glaciers of the Upper Gori Ganga basin has been given. The maximum altitude value was highest for Milam glacier, which is 6392 Masl, and lowest for Pachu glacier, which is 4694 Masl.

(iv) Length of Glacier (L)

It is the distance from the glacier's head or origin point to its terminus. The glacier length was measured along the central flow line of the glacier, from the highest point (maximum altitude) to the snout. Arc GIS 10.8.1 is used to identify the flow line and measuring its length. Among the observed glaciers, Milam glacier is the longest glacier in the basin, having 17.25 km length while Gonkha glacier is having shortest length which 2.29 km (Table 2).

(v) Width of glacier (W)

It is the maximum (widest) mean distance across the glacier at different points along the glacier outline, which is measured perpendicular to the flow direction. Variations in Glacier width indicate changes in glacier flow or external influences. For the 09 Glaciers of the Upper Gori Ganga basin, the width was measured at several representative points along their length, perpendicular to the flow line. The average width at specific locations was calculated. The maximum width was recorded for Milam glacier, which is 0.93 km, and the minimum width was recorded for Kalganga glacier in the Gonkha valley, which is 0.48 km.

(vi) Width of snout (Ws)

The actual glacier width at the snout is measurable in kilometers. The width of the glacier snout was measured perpendicular to the general flow direction at the terminus. The maximum snout width was measured for Shalang glacier, which is 1.15 km. the width of the snout for other observed glaciers is given in Table 2.

(vii) Area of Glacier (A)

The region bounded by the glacier outline is called the glacier's area. The glacier boundary was delineated on the Google Earth satellite imagery using visual interpretation. The area enclosed by the boundary was then calculated using GIS software. Among the observed glaciers, Milam glacier is the largest glacier in the basin having an area of 35.82 km2, and Shalang is the second largest glacier having an area of 11.3 km2. Gonkha is the smallest glacier having an area of

Table 2 : Illustration of glacial morphometric parameters

Glaciers	Z	Z	L	W	Ws	A	H	Rr	Eq	Si	ELA (0.45)
Milam Glacier	3580	6392	17.25	0.932	0.24	35.82	2812	163.01	0.05	0.25	4845.4
Shalang Glacier	3909	5787	12.2	0.701	1.15	11.3	1878	153.43	0.06	1.64	4754.1
Burphu Glacier	3943	5801	7.17	0.727	0.15	6.9	1858	398.61	0.01	0.2	4779.1
Kalganga Glacier	4093	5452	6.69	0.48	0.97	5.34	1359	203.14	0.07	2.02	4704.6
Rata Glacier	4611	5863	5.08	0.536	0.16	3.96	1252	246.46	0.11	0.3	5174.4
Gonkha Glacier	4772	5974	2.39	0.654	0.12	2.39	1202	502.93	0.27	0.18	5312.9
Bamlas Glacier	4473	5834	5.77	0.626	0.29	5.77	1364	236.4	0.11	0.46	5085.5
Pachu Glacier	3941	4694	7.87	0.524	0.24	4.08	753	95.679	0.07	0.45	4279.9
Timphu Glacier	4182	5672	7.62	0.467	0.17	3.9	1494	196.06	0.06	0.35	4852.5

z = Altitude of snout, **Z** = Maximum altitude, **L** = Length, **W** = Width, **Ws** = Width of snout, **A** = Area, **H** = Relief, **Rr** = Relief Ratio, **Eq** = Elongation Quotient, **Si** = Snout Index, **ELA** = Equilibrium Line altitude.

2.39 km2 (Table 2).

(viii) Relief (H)

Glacier relief was calculated as the difference between the maximum altitude and the altitude of the snout.

Formula - Relief = Maximum Altitude – Altitude of Snout

Table 2 shows the maximum relief calculated for Milam glacier, which is 2812 m, while minimum relief was calculated for Pachu glacier, which is 753 m.

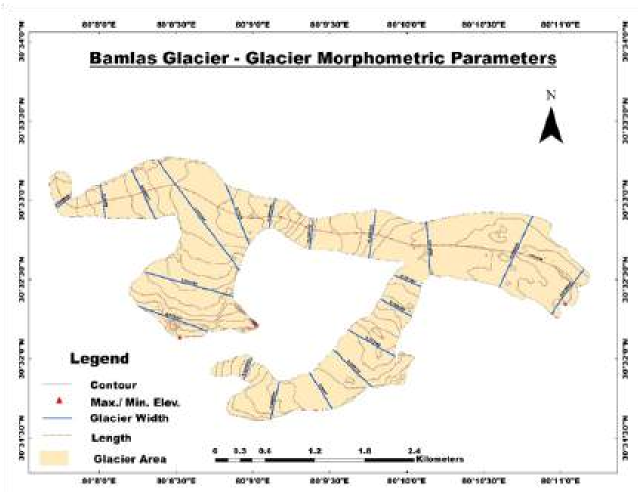

Fig.3: Illustration of glacial morphometric parameters over the glacier outline.

(ix) Relief ratio (Rr)

The relief ratio is the ratio of the glacier relief to its length. The highest relief ratio was calculated for Burpu glacier (398.61), and the lowest was calculated for Pachu glacier, which is 95.679 (Table 2).

Formula - Relief Ratio (Rr) = Relief (H) / Glacier Length (L).

(x) Elongation quotient (Eq)

Elongation Quotient (Eq) is the ratio between the mean width and maximum length of the glacier. This parameter describes the shape of the glacier. The highest Eq value is measured for Gonkha Glacier which is 0.27 and lowest value 0.01was recorded for Burphu glacier. All observed glaciers have Eq values lower than one, so it can be interpreted that the most of the glaciers in the basin are having elongated shape (table 2).

Formula - Elongation Quotient (Eq) = W / L.

Statistical Analysis

Regression analysis was performed on Relief ratio (Rr), Elongation Quotient (Eq), and Snout index (Si) in relation to Equilibrium Line Altitude (ELA). The values of Rr, Eq, and Si were plotted on a graph with ELA serving as the reference line to determine their relationship. Regression lines were then drawn. In this analysis, Rr, Si, and Eq function as independent variables, while ELA is regarded as the dependent variable. Table 3: Regression Analysis

(i) ELA vs. Relief Ratio (Rr)

A moderate positive linear relationship is observed, suggesting that as Rr increases, ELA also tends to increase. The regression line equation is: ELA = 1.54•Rr + 4644.83, with an R^2 value of 0.398, indicating that approximately 40% variation in ELA may be due to the relief ratio.

(ii) ELA vs. Snout Index (Si)

A weak negative trend is noticeable. The regression line equation is: ELA = -142.92 • Si + 5113.42, with R^2 = 0.097, indicating 9.7% of the variation in ELA is associated with Si. The scattered data points reflect inconsistency and low predictive power.

(iii) ELA vs. Elongation Quotient (Eq)

A moderate positive relationship is identified. The regression

Table 3: Regression Analysis

Independent Variable	Equation	Slope	Y-Intercept	X-Intercept	Relationship	R2 Values	Interpretation
Rr	ELA = 1.54•Rr + 4644.83	+1.54	4644.83	-3016.23	Positive	0.398	~39.8% of the variation in ELA is explained by Rr (Moderate correlation)
Si	ELA = -142.92•Si + 5113.42	-142.92	5113.42	35.78	Negative	0.097	~9.7% of the variation in ELA is explained by Si (Very weak correlation)
Eq	ELA = 2372.40•Eq + 4807.01	+2372.40	4807.01	-2.03	Strong Positive	0.314	~31.4% of the variation in ELA is explained by Eq (Moderate correlation)

Table 3 and Figure 4 present three distinct regression scatter plots that depict the relationship between ELA (the dependent variable) and three morphometric parameters (Rr, Si, and Eq).

line reads: ELA = 2372.40 • Eq + 4807.01, with R^2 = 0.314, suggesting that approximately 31.4% of ELA variation is due to the glacier's elongation quotient, indicating that broader glaciers (higher Eq) generally display higher ELAs. The Relief Ratio is the most significant explanatory variable for ELA, followed by the Elongation Quotient, while the Snout Index has a minimal effect. These findings emphasize the role of glacier geometry and slope in determining the altitude at which glaciers achieve equilibrium between accumulation and ablation.

INTERPRETATION

The morphometric parameters of nine glaciers are calculated and analysed. The analysis reveals that Milam Glacier has the largest area (35.82 km²), length (17.25 km), and maximum relief (2812 m). In contrast, Gonkha Glacier is the smallest in area (2.39 km²) and Kalganga Glacier has the narrowest average width (0.48 km). The widest snout is found at Shalang Glacier (1.15 km). Relief values range from 753 m (Pachu Glacier) to 2812 m (Milam Glacier)., Burphu Glacier showing the highest Relief Ratios (Rr) of 398.61 whereas Pachu Glacier shows a lowest Relief Ratios (Rr) of 95.68. in general Relief Ratios (Rr) vary considerably. All glaciers had Elongation Quotient (Eq) values below 1, indicating an elongated shape; Gonkha Glacier had the highest Eq (0.27), while Burphu Glacier recorded the lowest (0.01). ELA values spanned from 4279.9 m (Pachu Glacier) to 5312.9 m (Gonkha Glacier). It is calculated using the Area Accumulation Ratio (AAR) method with linear interpolation for AAR values of 0.45, 0.55, and 0.65. A regression analysis is carried out to identify the inter relationship between ELA and three morphometric variables i.e. Relief Ratio (Rr), Snout Index (Si), and Elongation Quotient (Eq).

CONCLUSIONS

The morphometric analysis of nine glaciers in area presents valuable insights into their physical characteristics and climate sensitivity. The variation in glacier area, length, and width signifies diverse glacial morphologies in the basin. The predominantly elongated shapes of most glaciers, as indicated by low Eq values, suggest confinement within narrow valleys a typical characteristic of the Himalayan glaciers. Milam Glacier, being the largest and longest, displays significant topographic influence and likely holds considerable climatic relevance. Smaller glaciers like Gonkha and Rata may be more susceptible to short-term climatic changes due to their reduced mass and lower accumulation potential. ELA serves as a sensitive indicator of climatic changes: higher ELA values (e.g., Gonkha, Rata) suggest glaciers are in more ablation-prone environments, whereas lower ELA values (e.g., Pachu, Shalang) indicate colder conditions favourable for accumulation. The variance in ELA across the glaciers may reflect microclimatic differences and topographic constraints. The regression analysis suggests that Relief Ratio (Rr) and ELA are having positive correlation, implying that glaciers with steeper profiles tend to have higher ELAs, as steeper glaciers may lose mass more efficiently through ablation at lower elevations. The Elongation Quotient (Eq) also displays a moderate positive correlation with ELA, suggesting that broader glaciers tend to have higher ELAs, potentially due to accumulating less snow along their length and achieving equilibrium at higher altitudes. Conversely, the Snout Index (Si) shows a very weak negative correlation with ELA, indicating that snout width does not strongly predict ELA position. The morphometric and regression analyses suggest that glacier geometry, especially relief and shape, influences ELA positioning, affecting glacier health and response to climate. These findings enhance understanding of glacier behaviour in varying topographic and microclimatic contexts.

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TOWARDS A ZERO-WASTE FUTURE: RETHINKING SOLID WASTE MANAGEMENT IN THE FRAGILE KULLU-MANALI HIMALAYAS

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ABSTRACT

The Kullu-Manali region of Himachal Pradesh, celebrated globally as a premier Himalayan tourist destination, is at the frontline of an escalating environmental crisis rooted in plastic pollution (Sarkar *et al.,* 2023; Kumar *et al.,* 2022). This issue, while superficially visible in the form of litter-strewn landscapes, harbors deeper ecological risks including microplastic infiltration of alpine soils, leaching of toxins into pristine river systems, and cascading impacts on biodiversity and human health. The situation is exacerbated by surging tourist inflows, constrained municipal resources, and the logistical constraints intrinsic to mountainous topographies. Waste management in the region remains tethered to an outdated paradigm centered around a single, overburdened landfill at Rangri, incapable of handling bote volume and heterogeneity of wastes produced. This study applies a multi-method research design encompassing empirical waste audits, GIS-based spatial analysis, semi-structured stakeholder interviews, and detailed policy reviews. Finngs reveal systemic breakdowns across the linear model of waste governance—collection, segregation, transportation, and disposal. In response, the study proposes a decentralized Integrated Solid Waste Management (ISWM) framework adapted to mountain contexts, emphasizing source-level segregation, community composting, material recovery facilities, technological interventions, and the recognition of informal waste workers as legitimate stakeholders. The paper further underscores that technological remedies, though necessary, are insufficient without parallel policy enforcement, producer accountability, eco-tourism promotion, and transformative community education. Situating Kullu-Manali within global experiences from other mountain regions (Waste Warriors, 2022; UNEP, 2018), the study concludes that transitioning toward a circular economy is the only sustainable pathway to safeguard both ecological integrity and socio-economic well-being in the fragile Himalayas.

INTRODUCTION

The Himalayas, often characterized as the "Third Pole," contain vast reserves of snow and ice, second only to the polar regions in freshwater storage (Singh *et al.,* 2021). These ranges, spanning multiple countries, supply critical ecosystem services that sustain billions of people in South and East Asia. However, rapid transformations in tourism, urbanization, and consumption patterns have ushered in profound ecological stresses. Plastic pollution represents a particularly acute challenge due to the non-biodegradable and persistent nature of polymers, their ubiquity in consumer culture, and their capacity to fragment into micro- and nanoplastics (Napper & Thompson, 2020). The Kullu-Manali valley epitomizes this collision of natural beauty and anthropogenic pressures. Historically pastoral and agrarian, the valley is now inundated with several million tourists annually, outstripping its carrying capacity. Tourism has brought economic prosperity through hospitality, adventure sports, and transport services, yet it has simultaneously overwhelmed civic infrastructure. The surge in single-use plastics—ranging from polyethylene terephthalate (PET) bottles to multilayered snack packaging—has transformed the waste profile of the region (Kumar *et al.,* 2022). Unlike biodegradable waste that local communities traditionally managed through composting or livestock feeding, plastics accumulate in perpetuity within ecosystems. They litter landscapes, clog drains, and infiltrate waterways, creating visual blight and systemic ecological hazards. In situating the Kullu-Manali plastic crisis within broader global discourses on mountain sustainability (TERI, 2019; UNEP, 2018), this paper emphasizes the urgency of rethinking waste governance frameworks in fragile ecologies.

HISTORICAL CONTEXT OF WASTE AND PLASTICS IN HIMACHAL PRADESH

Until the 1980s, the waste stream in Himachal Pradesh was overwhelmingly organic (TERI, 2019). Household refuse was comprised largely of vegetable residues, crop byproducts, firewood ash, and biodegradable fibers. These materials were either composted, reused within households, or consumed by domesticated animals. The system, though informal, aligned with principles of circularity and exhibited negligible ecological externalities. The economic liberalization of India in the 1990s and the proliferation of fast-moving consumer goods catalyzed a seismic shift in waste composition (UNEP, 2018). Plastics—lightweight, durable, and cheap—entered local markets in the form of bottled water, laminated snack packs, sachets, and synthetic textiles. This material transition disrupted traditional waste management practices. Himachal Pradesh was among the first states to recognize the impending crisis, enacting the Non-Biodegradable Garbage (Control) Act in 1995. Subsequently, the state pioneered a ban on plastic carry bags in 2009. Despite these progressive legal instruments, enforcement remained inconsistent (Municipal Corporation Kullu, 2022). Weak institutional capacity, inadequate infrastructure for alternatives, and entrenched consumer demand undermined policy objectives. Today, the Rangri landfill epitomizes the failures of incrementalism: initially conceived as a temporary repository, it has evolved into a hazardous, unmanaged dumpsite leaking contaminants into soil and waterways while emitting toxic fumes through frequent open burning (Kumar *et al.,* 2022). Also near the Kullu bus stand in Himachal Pradesh, waste has become a visible and pressing problem. Large heaps of garbage accumulate in and around the area, much of it consisting of plastic wrappers, bottles, and discarded bags. The smell of rotting waste mixes with the constant flow of travelers, creating an unpleasant environment for anyone passing through. The plastic waste in particular lingers on the streets, does not decompose, and adds to the growing piles that remain scattered for days. Stray animals are often seen rummaging through the heaps, tearing open plastic bags and spreading the trash further. The sight of plastic clogging drains and lying exposed in open spaces highlights how severely the surroundings have been affected. Over time, the area around the bus stand has developed a strong foul odor and a polluted atmosphere, making the problem hard to ignore. The historical trajectory demonstrates that legislative bans, in isolation, are insufficient (Dwivedy& Mittal, 2021). Effective reform requires integrated systems of collection, segregation, recycling, and behavioral change.

STUDY AREA: THE KULLU-MANALI CONTEXT

Kullu district, nestled within the western Himalayas, is defined by steep altitudinal gradients, riverine valleys, and fragile ecosystems (Singh *et al.,* 2021). Manali, situated at approximately 2,050 meters above sea level, functions as both a town and a gateway to high-altitude destinations such as Rohtang Pass and Lahaul-Spiti. The Beas River bisects the valley, providing irrigation, hydropower potential, and tourism opportunities such as rafting. The local climate is temperate with pronounced seasonality, including cold, snow-laden winters and warm summers. Solid waste generation in this region reflects three dominant characteristics: seasonality, composition, and transport constraints. Seasonality is marked by an exponential rise in waste generation during peak tourist seasons (April–July, October), often tripling baseline volumes. Compositionally, organics constitute the majority, but plastics account for nearly a quarter of total waste, with especially high contributions from hotels, restaurants, and retail outlets (Kumar *et al.,* 2022). Transportation challenges stem from the mountainous terrain, where narrow serpentine roads amplify fuel costs, accident risks, and delays. The Rangri landfill, located roughly 5 km from Manali, is chronically overburdened and situated perilously close to the Beas River, raising alarms regarding leachate contamination. The unique socio-ecological profile of Kullu-Manali demands waste solutions that diverge fundamentally from conventional, centralized urban models (Waste Warriors, 2022).

METHODOLOGY

The study employed a practical mixed-methods approach combining waste audits, spatial assessment, stakeholder interviews, and policy review (UNEP, 2018; TERI, 2019). Waste audits were undertaken at five strategically chosen collection points, including marketplaces, residential areas, and a hospitality cluster. Each sample was manually segregated into broad categories such as organics, plastics, paper, metals, glass, and inert matter, enabling an assessment of waste composition and general trends. A spatial component complemented this work through the use of Google Maps to mark collection points and note accessibility challenges, including steep gradients, narrow lanes, and traffic congestion. To capture local perspectives, ten semi-structured interviews were conducted with stakeholders such as municipal staff, sanitation workers, shopkeepers, hotel owners, and community members. These discussions revealed everyday challenges, informal practices, and local coping strategies. Finally, a review of policy instruments, including the Plastic Waste Management Rules (2016, amended 2021) and Himachal Pradesh's state-level plastic ban, was carried out to contextualize the findings within the broader regulatory framework. By integrating quantitative, spatial, qualitative, and policy perspectives, the methodology provided a well-rounded understanding of waste management dynamics and existing gaps.

FINDINGS: BREAKDOWN OF THE CURRENT SYSTEM

The current waste management architecture in Kullu-Manali is characterized by a linear collect, transport, and dump paradigm that is both unsustainable and ecologically hazardous (Dwivedy& Mittal, 2021). First, source segregation is virtually nonexistent. Despite intermittent awareness drives, most households and hotels continue to discard mixed waste, rendering recyclable fractions contaminated and economically unviable. Second, the Rangri landfill functions as an unscientific open dump. It lacks leachate collection systems, engineered liners, or methane capture infrastructure. During monsoons, leachate runoff risks polluting the Beas River, while frequent open burning releases carcinogenic dioxins and furans (Sarkar *et al.,* 2023). Third, transportation inefficiencies dominate the system. Waste trucks traverse winding mountain roads, consuming excessive fuel, emitting greenhouse gases, and suffering frequent mechanical failures. Collection schedules are irregular, further eroding public trust. Fourth, institutional constraints hamper efficiency. Municipal bodies operate under chronic financial deficits, inadequate staffing, and outdated machinery. Seasonal tourist influxes exacerbate these limitations, often overwhelming available infrastructure (Municipal Corporation Kullu, 2022). Finally, the informal sector, though instrumental in salvaging plastics and metals, operates in hazardous, unregulated conditions. Waste pickers lack protective gear, social security, or formal recognition, yet their recovery efforts substantially reduce landfill inflows (Waste Warriors, 2022). Collectively, these failures depict a governance system locked in a cycle of crisis management rather than systemic resilience (Kumar *et al.,* 2022).

COMPARATIVE INSIGHTS: LESSONS FROM OTHER MOUNTAIN REGIONS

Lessons from other mountainous regions, both within and outside South Asia, highlight alternative models (UNEP, 2018; TERI, 2019). Dharamshala, for instance, piloted decentralized composting at ward levels, effectively reducing organic loads but struggling to scale operations sustainably. In Nepal, Everest trekking routes enforce strict "carry back your waste" regulations, showcasing the efficacy of mandatory frameworks supported by community enforcement. Bhutan integrates cultural and spiritual values into its policies, banning plastic bags under the philosophy of Gross National Happiness. Beyond South Asia, European alpine towns like Zermatt, Switzerland, exemplify holistic approaches. There, community buy-in, advanced infrastructure, and policy integration have enabled near-zero-waste outcomes, incorporating anaerobic digestion and energy valorization systems (Zaman & Lehmann, 2013). These examples highlight core transferable insights: the necessity of strong regulatory frameworks, community engagement, recognition of informal labor, and technological innovation. Nonetheless, transposition requires adaptation to local socio-economic realities in Kullu-Manali, where fiscal resources and institutional capacities differ significantly.

PROPOSED FRAMEWORK: DECENTRALIZED ISWM FOR KULLU-MANALI

Addressing systemic inefficiencies necessitates a paradigm shift toward decentralized Integrated Solid Waste Management (ISWM) (Kumar *et al.,* 2022; TERI, 2019). The proposed framework rests upon six interconnected pillars:

- Mandatory source segregation, enforced via two- or three-bin systems, incentivized by penalties and rewards.
- Establishment of community-level composting and vermin composting units, producing nutrient-rich compost for local orchards and farms.
- Creation of strategically located Material Recovery Facilities (MRFs) to sort, bale, and market recyclables, with low-value plastics diverted to cement kilns under EPR schemes (Dwivedy& Mittal, 2021).
- Deployment of technological innovations, including compactors and balers, particularly at high-volume tourist sites, to reduce waste volume and transport costs.
- Formal recognition and integration of informal waste workers into municipal systems, providing contracts, protective gear, and training (Waste Warriors, 2022).
- Minimization of landfill dependency by restricting landfill inputs to inert and non-recyclable residues, aiming to reduce volumes by over 90%.

Collectively, this framework offers ecological resilience, economic efficiency, and social justice.

Policy, Education, and Tourism Synergies

The success of ISWM in Kullu-Manali hinges on synergistic integration of policy, education, and tourism (UNEP, 2018). Policy instruments must strengthen municipal bylaws to mandate segregation, enforce bans on single-use plastics, and ensure strict compliance with Extended Producer Responsibility (EPR) regulations (Dwivedy & Mittal, 2021). Economic instruments such as a "green fee" levied on hotels and tour operators can generate dedicated funds for waste infrastructure. Educational campaigns, multilingual and culturally tailored, should target both residents and tourists, with school curricula embedding waste literacy for intergenerational impact. The tourism industry must adopt eco-certification programs, rewarding environmentally responsible practices while penalizing non-compliance. Adventure agencies and trekking groups should enforce "Leave No Trace" principles, supported by community watchdogs. This tripartite strategy of governance, education, and industry alignment is critical to embedding sustainability into the socio-economic fabric of the region (TERI, 2019).

Socio-Cultural Dimensions of Waste Practices

Waste practices are deeply rooted in socio-cultural dynamics (Singh *et al.,* 2021). Traditional households, particularly in rural zones, continue composting organics, but urbanization has disrupted these practices. Religious rituals and temple tourism contribute substantially to waste, with offerings often disposed directly into rivers, intensifying pollution (TERI, 2019). Cultural notions of purity and pollution shape community attitudes, often relegating waste handling to marginalized groups. Reforms must therefore be culturally sensitive. Framing community composting as a revival of traditional practices may increase adoption, as it reconnects people to long-standing ecological ethics. Religious leaders can be engaged as champions of environmental stewardship, aligning river-cleaning initiatives with sacred duties. This approach has shown success in other Himalayan regions where faith-based environmental campaigns mobilized public participation (Waste Warriors, 2022). Gender dynamics further complicate the picture. Women traditionally manage household composting, while men dominate municipal waste operations. Inclusive reforms must ensure equitable participation and benefits across gendered roles (UNEP, 2018). Capacity building, micro-enterprise opportunities, and formal recognition for women in waste cooperatives can further strengthen community resilience.

Climate Change Linkages

Plastic pollution intersects with climate change in multiple dimensions (Sarkar *et al.,* 2023). Open burning of plastics emits black carbon, a potent short-lived climate forcer that accelerates Himalayan glacial retreat when deposited on ice. Leachate from unlined landfills infiltrates alpine aquifers and rivers, degrading water quality and undermining aquatic resilience in ecosystems already stressed by rising temperatures. Microplastics compromise fish populations and bioaccumulate in food chains, threatening local livelihoods and downstream populations dependent on Himalayan rivers (Napper & Thompson, 2020). Additionally, inefficient transport systems exacerbate greenhouse gas emissions, compounding vulnerabilities. Addressing waste management is thus simultaneously an ecological imperative and a climate adaptation measure, enhancing resilience against cascading threats of glacier retreat, altered hydrological cycles, and biodiversity loss (Singh *et al.,* 2021; Kumar *et al.,* 2022).

CONCLUSION AND RECOMMENDATIONS

The Kullu-Manali case illustrates the convergence of global environmental challenges within a single fragile valley: plastic pollution, unsustainable tourism, and climate vulnerabilities (Kumar *et al.,* 2022). Decentralized ISWM emerges as the most viable solution, integrating ecological, social, and economic imperatives (TERI, 2019).

Key recommendations include

Piloting ward-level ISWM projects, integrating waste segregation, composting, and recycling.

Forming multi-stakeholder task forces that include municipal officials, NGOs, and local communities.

Mobilizing EPR funds to support infrastructure and recycling units (Dwivedy & Mittal, 2021).

Investing in compactors and MRFs to reduce landfill dependency.

Formalizing informal waste workers, providing contracts, social protection, and safety equipment.

Embedding eco-certification within tourism, linking sustainability to brand and reputation.

Equally important are cultural framing of reforms and integration of climate strategies. Safeguarding the Himalayas demands systemic reform, adaptive governance, and sustained community engagement (UNEP, 2018; Waste Warriors, 2022). By learning from global exemplars while tailoring interventions to local realities, Kullu-Manali can transition into a zero-waste tourism model, preserving both ecological integrity and sustainable livelihoods (Zaman & Lehmann, 2013).

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GEOSPATIAL ANALYSIS OF PLASTIC POLLUTION IN THE GANGA RIVER USING REMOTE SENSING AND GIS TECHNIQUES

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ABSTRACT

The present study examines plastic pollution in the Ganga River, focusing on the Haridwar stretch, through the integration of Remote Sensing (RS) and Geographic Information System (GIS) techniques. Using Sentinel-2 multispectral data, spatial and seasonal variations in water quality were assessed through the Normalized Difference Chlorophyll Index (NDCI) and Biochemical Oxygen Demand (BOD) for the year 2024. Results show distinct seasonal patterns, with higher chlorophyll and BOD concentrations during pre- and post-monsoon periods when reduced flow, religious gatherings, and waste discharge intensify pollution. Three-dimensional terrain analysis revealed that slope and runoff play a key role in directing plastic waste from urban areas into the river channel. The combined trends of NDCI and BOD indicate a strong link between plastic accumulation, nutrient enrichment, and oxygen depletion, emphasizing the dual impact of human activity and hydrological conditions on river health. The study demonstrates the value of RS and GIS as efficient tools for large-scale water quality monitoring. It further suggests practical interventions such as reinforcing Extended Producer Responsibility (EPR), promoting compostable alternatives, and adopting plastic-to-fuel conversion methods to reduce waste inflow. These insights contribute to the broader goals of the Namami Gange Mission and support sustainable river management within the Ganga basin.

Key words: Central Himalaya, Glacier, Equilibrium Line Altitude (ELA), Morphometry, GIS.

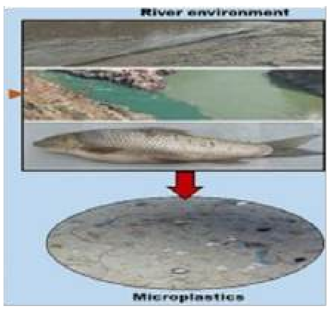
INTRODUCTION

Plastic pollution has become one of the most harmful environmental threats in recent times, affecting rivers, lakes, and oceans across the globe. Among the freshwater bodies facing significant stress, the Ganga River stands out because of its cultural, economic, and ecological importance, along with the heavy pollution it endures. Stretching over 2,500 kilometers, the Ganga has long been a source of water for domestic, agricultural, and industrial use for millions of people in northern India. In 2008, the Indian government recognized its historical, spiritual, and ecological significance by designating it a National River. In recent years, however, the river has faced increasing pressure from plastic waste entering from various sources — including urban runoff, industrial discharge, religious offerings wrapped in man-made materials, and the improper disposal of household trash. The situation worsens during the monsoon season, when heavy rains and floods sweep large quantities of accumulated plastic waste from land into the river. The Ganga is among the top ten rivers contributing to marine plastic pollution worldwide, with estimates suggesting that around 0.12 million tons of plastic enter the ocean from it each year. (Sarkar *et al.,* 2022) The ecological impact of this pollution is extensive.

Plastic waste alters the riverbank environment by covering soil, affecting erosion and water infiltration. Floating waste and micro plastics reduce water quality, making it unsuitable for drinking and increasing the cost of treatment. When plastic accumulates in vegetation areas along the floodplain, it interferes with plant growth, disrupts nutrient cycling, and damages habitat. For aquatic life, the effects are even more severe — fish, turtles, and other species can become entangled in plastic, resulting in injury, reduced reproduction, and death. Studies have found plastic particles ingestion was recorded nearly 260 marine species, including mammals, fish, turtles, invertebrates, and seabirds. Total species affected by marine debris – 914 species through ingestion and /or entanglement (Kühn & Van Franeker, 2020).

The risks extend beyond wildlife, with research showing that micro- and nanoplastics have been found in various human organs and tissues. the recent detection of MNPs in human blood, placenta and brain tissue Micro- and nanoplastic (MNP) pollution is now recognized as a global issue, but the data we have is still scattered and inconsistent.(Koelmans *et* *al.,* 2019) pointed out that differences in research methods make it difficult to properly assess the risks. For example, a study on tap water found that 81% of samples worldwide contained microplastics, with an average of 5.45 particles per liter(Kosuth *et al.,* 2018). Another study on bottled water showed even higher contamination—93% of bottles tested had microplastics, averaging 325 particles per litter, and in some brands the number went above 10,000 particles per litter (Mason *et al.,* 2018).

These particles may trigger oxidative stress, inflammation, endocrine disruption, and metabolic disorders, though the full extent of their health effects is still being studied. Overtime, microplastics can enter the food chain, leading to continuous exposure for both humans and animals.Public health interest in microplastics has grown rapidly across the globe (Balda *et al.,* 2025).



Traditional field methods for monitoring pollution are time-consuming and limited in spatial coverage. This is where Remote Sensing (RS) and Geographic Information Systems (GIS) offer a better alternative. Satellite data provides synoptic, repeated, and cost-effective information for assessing water quality over large areas and over time. Multispectral sensors can be used to analyze plastic pollution in combination with bio-physical indicators like chlorophyll and Biochemical Oxygen Demand (BOD). This study focuses on the Haridwar region, where religious activities and poor waste management significantly affect water quality.

OBJECTIVES

•To analyze spatial and seasonal changes in chlorophyll and BOD in the Haridwar stretch of the Ganga River using remote sensing techniques.

•To use 3D elevation modeling to study how topography and slope affect the flow and deposition of waste during rainfall events.

•To identify pollution hotspots and areas where plastic waste accumulation is highly correlated with water quality indicators.

To evaluate the effectiveness of Remote Sensing and GIS as tools for continuous monitoring and management of plastic pollution in river systems.

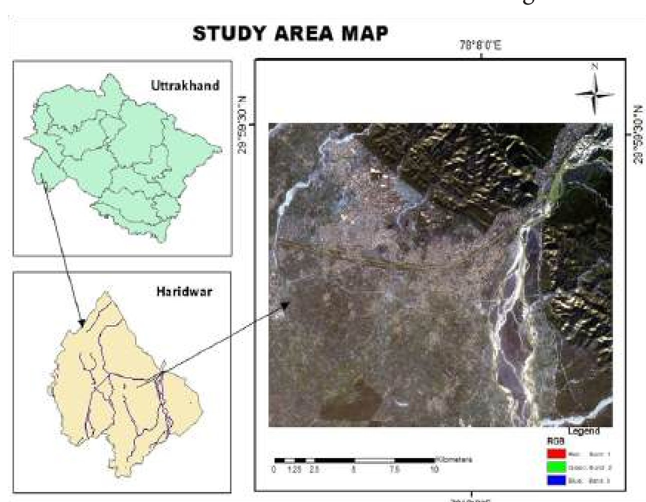
METHODOLOGY AND METHOD

STUDY AREA

The Himalayas are the main source of rivers like the Ganga. The study area is the Ganga River in Uttarakhand, focusing particularly on the region between Haridwar and Rishikesh because of its cultural and economic importance. This stretch faces significant stress due to plastic pollution. The river supports drinking water supply, irrigation, fisheries, religious practices, and tourism. Millions of pilgrims visit these cities each year for rituals, ceremonial baths, and festivals like the Kumbh Mela, considering the river sacred. The Ganga also supports diverse ecosystems, sustaining aquatic species, riparian vegetation, and agricultural activities along its banks. The region experiences heavy tourism, especially during pilgrimage and river festivals, combined with urban expansion, leading to increased generation of single-use plastics. These plastics enter the river, contributing to pollution. The study was conducted in a rectangular section of the Ganga River and its surrounding landscape in the Haridwar region, Uttarakhand. The study area includes the river channel and adjacent urban and semi-urban zones where solid waste discharge and runoff are common. The rectangular extent was chosen to ensure complete coverage of the target stretch in available satellite imagery and to capture both the main river flow and related land uses that impact water quality.

MONITORING GANGA RIVER

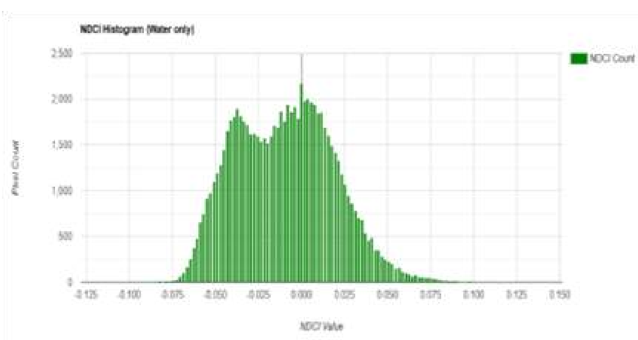
Monitoring the Ganga River involves several parameters to assess pollution levels and water quality, as plastic pollution is one of the most visible contributors to river degradation.



Normalized Difference Chlorophyll Index (NDCI)

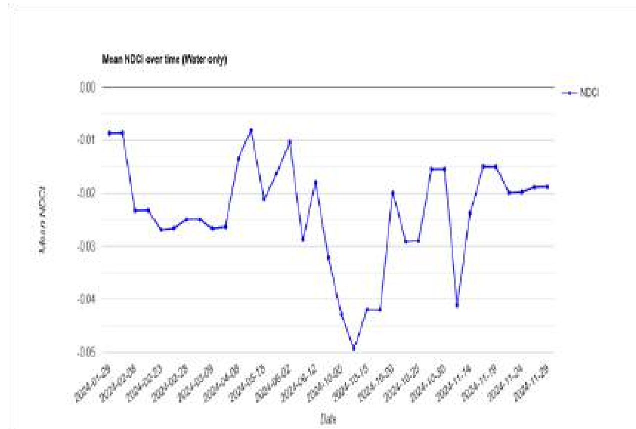
Plastic pollution affects chlorophyll levels in rivers through various mechanisms. Floating plastics and suspended micro plastics block light, reducing photosynthesis and leading to lower chlorophyll levels. At the same time, plastics can transport nutrients that promote algal growth, potentially increasing chlorophyll levels in some areas. Overall, plastic pollution can both suppress and stimulate algal growth, with the net effect depending on the type, concentration, and environmental conditions of the river system. Seasonal variation significantly affects microplastic distribution in the upper Ganga River (Chaudhary et al., 2025). The Normalized Difference Chlorophyll Index (NDCI) is a new model designed to estimate chlorophyll concentration in turbid, productive water. It is calculated using the red spectral band (B4) and the red edge spectral band (B5), with the formula: NDCI = (B5 – B4) / (B5 + B4).

VISUALIZATION OF CHLOROPHYLLIN GEE (GOOGLE EARTH ENGINE) USING SENTINEL -2 SATELLITE DATA (TOA)



Observations of the Ganga River near urban zones in Haridwar indicate moderate to high chlorophyll levels, suggesting that chlorophyll is elevated downstream. This could be due to plastic-related nutrients and external pollution sources like urban sewage, temple waste, agricultural runoff, and tourism pressure, which encourage algal growth more than the light-blocking effects of plastic. Recent studies have shown that Rishikesh and Haridwar ganga river have some of the highest microplastic concentrations in the upper reaches of the river, around 100 and 1550 particles/L (water) and 50 and 1300 particles/Kg(sediment) (Kaparapu & Geddada, 2015)

TIME SERIES CHART OF CHLOROPHYLL CONTENT IN GANGA RIVER OF 2024



The time series analysis of NDCI shows clear seasonal fluctuations throughout the year 2024. The index values mostly range between –0.01 and– 0.05,Higher NDCI values were observed during the pre-monsoon (March–April) and early monsoon (May–June), suggesting enhanced chlorophyll due to nutrient inflow and favourable growth conditions .A sharp decline in NDCI occurred during mid-October, reaching its lowest point (~ –0.05), possibly due to increased turbidity and sediment load after heavy monsoon discharge, which suppresses chlorophyll signal Post-monsoon (November–December) shows stabilization of NDCI values, indicating gradual recovery of chlorophyll after the monsoon effect. Overall, the NDCI time series highlights the influence of seasonal hydrology and waste input on chlorophyll dynamics in the Ganga River near Haridwar.

Reasons of Chlorophyll spike during pre-monsoon and early monsoon could be-

Low Flow and High Temperature (Pre-Monsoon, April–June) Water levels are relatively low because snowmelt is just beginning and monsoon hasn't started. High summer temperatures enhance biological activity. Warm and stagnant water favors algal growth, leading to higher chlorophyll.

Tourism & Pilgrimage Pressure (Pre-Monsoon, May–June) Haridwar sees huge influx ofpilgrims during festivals (e.g., Ganga Dussehra, summer bathing rituals). Large-scale religious bathing and offerings (flowers, food, plastics) increase nutrient input into the river. Extra nutrients (nitrogen, phosphorus) promote phytoplankton/algal blooms, reflected in rising NDCI.

BIOCHEMICAL OXYGEN DEMAND (BOD)

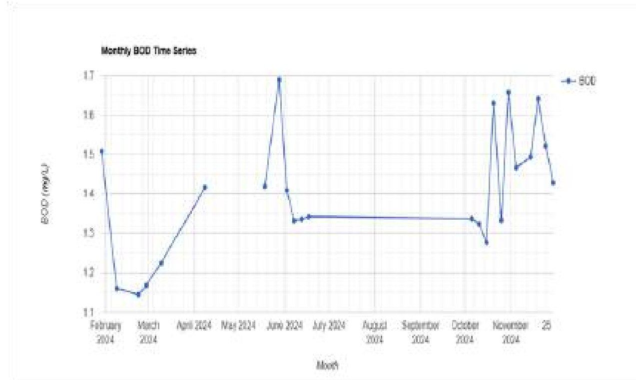
BOD measure the amount of oxygen required by microorganisms that decompose organic matter in water. High BOD means low oxygen availability, which can harm aquatic life. Plastic pollution is not biodegradable, but it affects BOD in several ways- Biofilm formation increase the BOD because plastic provide surface for microbial colonies, which consume oxygen, Organic adsorption also leads BOD plastic trap organic pollutants that increase microbial activity. Another one is micro plastic ingestion. Aquatic organisms ingest plastics, leading stress and decay, which raises BOD. Mass bathing during Ardhkumbh significantly altered the water quality of the Ganga, introducing elevated levels of organic and microbial pollutants. religious gatherings can strain aquatic ecosystems, urging better management practices.(Kulshrestha & Sharma, 2006)

BOD level in ml/letter	Water quality
1-2	**Very good:** there will not be much organic matter present in the water
3-5	**Fair:** moderately clean
6-9	**Poor:** somewhat polluted –usually indicate that organic matter present and microorganisms are decomposing that west
100 or more	**Very Poor:** Very polluted contains organic matter

VISUALIZATION OF BOD IN GEE USING SENTINEL-2 SATELLITE DATA (TOA, 2024)

This visualization of BOD absorbs that the urban zone of Ganga River in Haridwar is leading more BOD in compare to upper side zone. Central part of river that away from its band that are moderately clean but the river band or riverside are poor condition means led to high BOD (low oxygen availability). The Biological Oxygen Demand (BOD) values in the Ganga River at Haridwar during 2024 showed noticeable seasonal variations. In the early months (February–March), BOD was relatively higher (~1.5 mg/L) but dropped to its lowest (~1.2 mg/L) in March, possibly due to dilution from late winter flows. From April to June, BOD gradually increased, peaking in June (~1.7 mg/L), which may be linked to rising temperatures and increased organic matter load prior to the monsoon.

During the monsoon (July–September), BOD levels stabilized around ~1.3–1.4 mg/L, likely due to the flushing effect of high

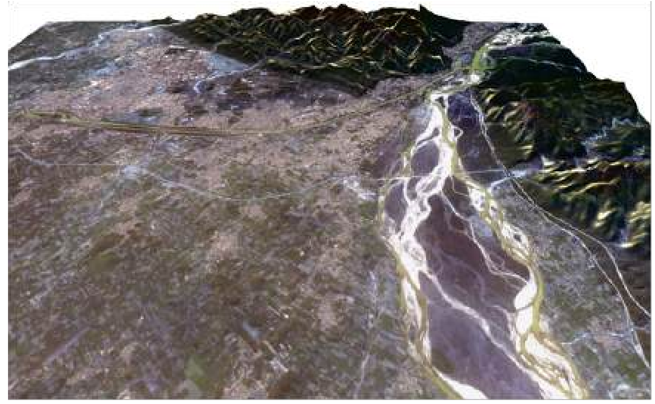


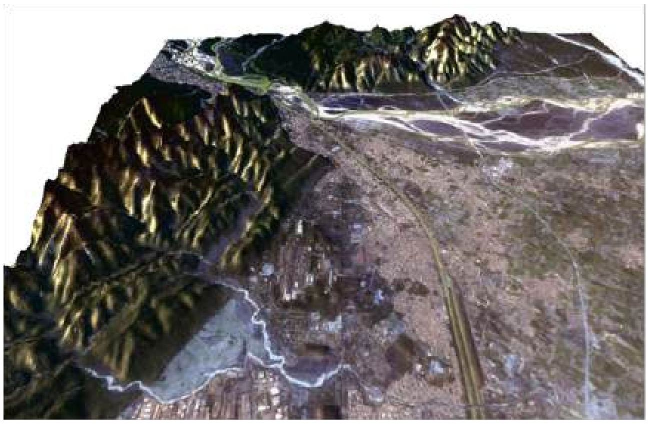
river discharge that diluted organic pollutants. However, in the post-monsoon and late year (October–November), BOD values again spiked (>1.6 mg/L at several points), which could be attributed to reduced flow, accumulation of waste, and increased pilgrim and festival activities in Haridwar during this season.

Overall, the pattern suggests that BOD increases during pre-monsoon and post-monsoon periods, while it decreases during peak monsoon months due to dilution. The observed fluctuations are strongly influenced by seasonal hydrology, temperature, and human activities along the riverbank.

3D PERSPECTIVE VIEW

It shows the elevation differences that can identify the flow of dump waste (plastic) and runoff flow downhill during rainfalland eventually enter the Ganga River. Haridwar lies at the foothills of the Shivalik range, where the Ganga emerges from the mountains onto the plains. This transition creates a natural variation in elevation and slope, which plays an important role in the movement of waste materials during rainfall events. Low-lying areas act as waste accumulation zones, while steep slopes enhance the flow of dumped waste towards the river. To better understand this relationship, a 3D terrain visualization of the study area was created using a Digital Elevation Model (DEM) draped with satellite imagery. The visualization highlights how topography influences surface runoff, drainage patterns, and the transport of plastic and organic waste into the river system.





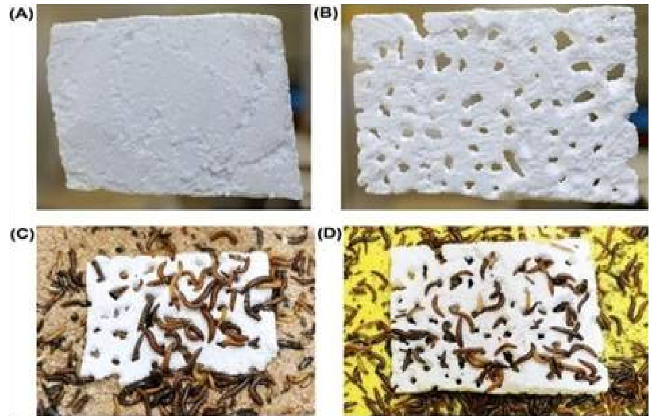
DISCUSSION AND RESULTS

These findings highlight the need for plastic waste management strategies, planning for River Rejuvenation to reviving or restoring the natural flow and health of river that has been damaged due to human activity mainly waste dumping, encroachment and pollution. Ganga River which one part is flowing thorough urban zone showing poor health of river that mean increasing urbanization will increase the river pollution. The time series analysis of Normalized Difference Chlorophyll Index (NDCI) and Biological Oxygen Demand (BOD) for the year 2024 revealed distinct seasonal patterns in the Ganga River near Haridwar, strongly influenced by hydrological changes and anthropogenic activities. The combined trend of NDCI and BOD highlights a strong seasonal coupling between algal productivity and organic pollution. Higher chlorophyll (NDCI) levels are associated with increased BOD, suggesting that nutrient enrichment and organic matter decomposition drive oxygen demand in the river system. The results clearly show that pre-monsoon and post-monsoon are critical periods when water quality deteriorates, while the monsoon season provides a natural flushing effect. Overall, the findings emphasize the dual role of natural hydrological cycles and human activities in controlling water quality dynamics in the holy Ganga River at Haridwar.

PROBLEM STATEMENT: Only 9% of plastic is recycled, 12% of plastics is incinerated, 79% of plastics is dumped into landfills, oceans or water bodies (Alabi *et al.,* 2019).

Some Sustainable Solution to Reduce Plastic Pollution

Plastic eating worm– Scientist have found a plastic eating worm that could be possible to reduce the plastic pollution. This warm is describe by nature .The larvae of a lesser-eating Kenyan mealworm can digest the ubiquitous pollutant, this is only insect species native to Africa that shown to eat plastic, the Conversation reported (Ndotono *et al.,* 2024). These insects naturally eat plastic, and by studying them, we hope to find faster and smarter ways to get rid of plastic waste, to find how these insect mechanisms are working to decompose the plastic in their stomach.



Styrofoam block before feeding (A), Styrofoam block after 30 days feeding and consumption of the polystyrene (PS) evident by the holes and tunnels formed (B), mealworms feeding on polystyrene and bran diet (C), mealworms feeding on sole Polystyrene diet (D).

Producer Responsibility– Producers and manufacturers should take responsibility for the lifecycle of plastic products. This includes collection, segregation, and recycling once the product is discarded. If companies that profit from plastic are made accountable, it can reduce the flow of single-use plastics into rivers. EPR (Extended Producer Responsibility) comes under the Plastic Waste Management Rules, 2016 Producers (Importers and Brand-owners) have responsibility to ensure processing of their plastic packaging waste through recycling, re-use or end of life disposal.(Colelli *et al.,* 2022)

Action Plan for fresh water Resource–The Government of India has already initiated programs like the Namami Gange Mission, which focuses on reducing pollution in the Ganga. These efforts can be strengthened by stricter enforcement of plastic bans, better solid waste management systems, and continuous monitoring of riverbank activities, especially during religious festivals in Haridwar. In this mission 200 project have be included under the budget of 13,110 crore and as of date116 project have been completed (Nava *et al.,* 2024) another one like Ministry of water Resources, River Development and Ganga Rejuvenation (India), Sadh guru 'Rally for River' (Isha Foundation), National Council for River Ganga Rejuvenation, protection and management and several NGOs and community group have been active to rising awareness about river pollution.

Conversion of plastic into petrol– Advances in pyrolysis technology now make it possible to convert certain plastics into useful fuels like petrol and diesel. Setting up small-scale units near major urban centers could help reduce the burden of non-recyclable plastics while creating a circular economy. (Chandran *et al.,* 2020)

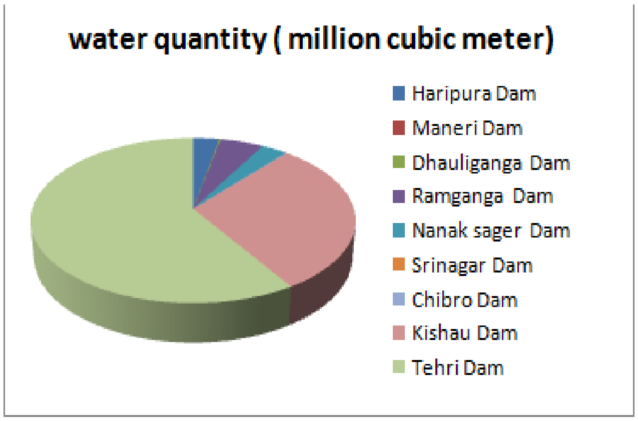
Compostable Plastic /Carry Bag– Promoting compostable carry bags and packaging can cut down on single-use plastics. Unlike traditional plastics that persist for decades, compostable materials break down naturally without leaving harmful residues in the water. Haridwar, being a pilgrimage city, can introduce these alternatives at ghats, markets, and religious events. Report from CPCB (Central Pollution Control Board), Compendium of Manufacturers/Sellers of Eco-alternatives to Banned Single Use Plastics (SUP) 2025. These are company who certified by CPCB. (nmcg.nic.in, n.d.)

Human Dependency on the Ganga River and Role of Dams
Several dams and barrages have been constructed along the ganga river and its tributaries in Uttarakhand. According to their water containing capacity we can assume that necessity of water to fulfill the human need. 500 million populations depend on Ganga River in the Genetic Plain. Toxic pollution is serious concern that time.

UTTARAKHAND CPCB CERTIFIED COMPOSTABLE PLASTIC CARRY BAGS/ COMMODITIES MANUFACTURERS/SELLERS

S NO.	Name of Company	Contact Details	Date of Issue of Certificate	Certificate (If Issued) (Provisional/ Final) (NA for Others)	Capacity (TPA)	Product As Per Application & Process Flow Diagram
1	Bioplastics India Private Limited	46, Sector-3, IIE Pantnagar, Rudrapur, Udham Singh Nagar, Uttarakhand – 263153	20.08.2024	One Time Certificate	1080	Compostable Carry Bags
2	Weener Empire Plastics Pvt. Ltd.	Weener Empire Plastics Pvt. Ltd. Address: Khasra No. 1379, Langha Road, Dist. Dehradun Contact: 7276743899 Email rohit.chavan@wppg.com	05.07.2023	One Time Certificate	18	Compostable Fork
3	ITC LTD	ITC Limited (Manufacturer) Address: ITC Ltd, Packaging and printing unit, Plot No:1, Sector-11, IIE, Sidcul, Haridwar, Uttarakhand249403. Contact:8754463553 Email:boobalan.r@itc.in	12.09.2024	One Time Certificate	6167	1. Bioseal coated stiffener paper, 2. Bioseal coated art paper, 3. Bioseal coated virgin board, 4. Bioseal coated paper, 5. Bioseal coated recycled board.
4	Karma Industries	Karma Industries Address: Plot No-133/1, Sirohi Farm, Fauji Matkota, Bhurarani Road, Rudrapur, Distt-U.S Nagar Uttrakhand-263153 Contact: 9105559993 Email: karma.industries@ rediffmail.com	18.09.2023	Provisional (Complete test report & EPR)	25	Compostable Carry bags
5	Maa Bhagwati Bioplast and Compostable	Maa Bhagwati Bioplast and Compostable (Manufacturer) Address: Khasra No. 651 & 652, Village Lalpur, Kunda Road, Jaspur,Us Nagar, Uttrakhand-244712 Contact Details: 7060400255 Email: shailja.mbhagwati@ gmail.com	01.02.2023	One Time Certificate	348	Compostable Carry bags
6	Organic Plast	Organic Plast (Manufacturer) Address: C-34, Sigaddi Growth Centre, Kotdwar, Uttarakhand-246149 Contact Details:9999719995 Email: Contact@Organicplast. Com	08.04.2022	Final (RC)/ (EPR)	720	Compostable Plastic Film and Sheet

Dams	Water quantity (million cubic meter)
Haripura Dam	132
Maneri Dam	0.5
Dhauliganga Dam	6.2
Rāmgangā Dam	219.6
Nanak Sagar Dam	132
Srinagar Dam	0.0264
Chibro Dam	5.11
Kishau Dam	1,324
Tehri Dam	2,615



CONCLUSION

This study assessed the relationship between plastic pollution and river health in the Ganga at Haridwar by analyzing biological oxygen demand (BOD), chlorophyll concentration, and seasonal variations during 2024. The findings highlight that periods of high plastic load, especially during pre-monsoon and early monsoon, coincided with noticeable fluctuations in chlorophyll and BOD. Plastic debris not only restricts light penetration and affects photosynthesis but also provides surfaces for algal growth, explaining the observed spikes in chlorophyll content. Similarly, organic waste carried along with plastics likely contributed to higher BOD values, indicating greater stress on the aquatic ecosystem. The results suggest that plastic waste in the river has a dual and complex role—sometimes suppressing photosynthetic activity and at other times accelerating it through nutrient enrichment. This duality underlines why localized monitoring is essential for a sacred and heavily used river stretch like Haridwar, where both natural flows and anthropogenic pressures shape water quality. While ongoing programs such as Namami Gange and local NGO efforts have made progress in cleaning the river, the persistence of plastic pollution demands more integrated solutions. Recommendations such as strengthening Extended Producer Responsibility, encouraging compostable alternatives, exploring plastic-to-fuel technologies, and expanding community-based awareness and monitoring can support long-term river health. In conclusion, the study reinforces that reducing plastic input into the Ganga is not only an environmental requirement but also a social and cultural necessity for the millions who depend on this river. A combined effort of government, industries, NGOs, and local communities is vital to ensure that the Ganga at Haridwar sustains its ecological integrity while continuing to serve as a lifeline for people, biodiversity, and spiritual heritage.

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PLASTICS FROM INNOVATION TO ENVIRONMENTAL CHALLENGE: TOWARDS CIRCULAR ECONOMY AND BIODEGRADABLE ALTERNATIVES

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ABSTRACT

A common substance in contemporary civilization, plastics find extensive use in a variety of sectors, including electronics and packaging. However, the swift rise in the production and consumption of plastics has resulted in a concerning surge in the amount of plastic waste produced around the world. This sharp rise is attributed to the global shift from reusable to single-use containers, which has accelerated the growth of plastics in the packaging industry. Addressing the issue of plastic waste requires a comprehensive approach that encompasses various strategies, such as improving waste management systems, promoting the development of biodegradable or recyclable plastics, and encouraging a shift towards a more sustainable and circular economy.

Key words: Polyhydroxyalkanoate Microplastics Circular Economy Single use plastic Sustainable Development

INTRODUCTION

The issue of plastic waste has become increasingly pressing in recent years as the global production and consumption of plastics continue to rise, leading to a significant accumulation of plastic waste in the environment (Patel *et al.,* 2021). Around 1.7 million tons of plastic were produced worldwide in 1950, 355 million tons in 2016, and 367 million tons in 2020. Its production is expected to cross 1,000 million tons by 2050 (Bhatia *et al.,* 2023). This has led to the accumulation of plastic waste in the natural environment particularly in aquatic ecosystems, where it is estimated that 4.8-12.7 million tonnes of plastic waste from land were discharged into the marine environment in 2010 (Patel *et al.,* 2021; Patel and Lee, 2022; Patil *et al.,* 2024). Microplastics, defined as plastic fragments smaller than 5 μm in size, can be formed through the fragmentation and degradation of larger plastic items over time (Leandro *et al.,* 2023). They can be consumed by various organisms, which may result in numerous detrimental effects on the ecosystem. For example, the presence of microplastics in the environment has been associated with the uptake of harmful chemicals, such as bisphenol A and phthalates, which are commonly used in plastic manufacturing and have been linked to negative health impacts in humans and wildlife, including infertility, cardiovascular diseases, and cancer plastics (Patel and Lee, 2022, Kalia *et al.,* 2023). To address the growing problem of plastic waste and microplastic pollution, a multipronged approach is necessary, involving improvements across the entire life cycle of plastics, from production to disposal. Many countries have already taken steps to address the issue, with over 120 countries implementing bans on selected single-use plastics. The issue of plastic waste and microplastic pollution has become a significant global challenge, with far-reaching environmental and health implications. Addressing this problem will require a comprehensive and coordinated approach, involving a range of stakeholders, including

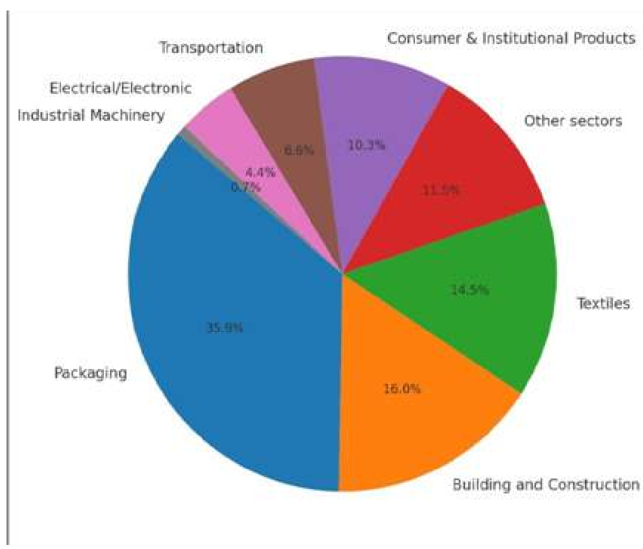

Fig. 1. Distribution of plastic consumption across different sectors worldwide.

governments, businesses, and individual consumers.

CIRCULAR ECONOMY

A circular economy represents an economic system designed to minimize waste and resource usage by encouraging the repurposing and recycling of products. Implementing circular economy policies through the recycling of domestic waste is crucial to mitigate the harmful effects of pollution (Sahin and Kirim 2018). The goal of a circular economy is to keep plastics in use for as long as possible, extract the maximum value from them, and recover and regenerate materials at the end of their service life. Some benefits of a circular economy for plastics include:

•Reduced greenhouse gas emissions.
•Conservation of natural resources.
•Decreased plastic waste in oceans and landfills.
•Creation of new economic opportunities and jobs.

PHA : A BIODEGRADABLE ALTERNATIVE

Polyhydroxybutyrate (PHB) is a simple kind of biodegradable and biocompatible polyhydroxyalkanoate (PHA) polymer that is produced by various microorganisms as an intracellular carbon and energy storage compound (Senko *et al.,* 2023). It has gained significant attention in recent years as a potential alternative to petroleum-based plastics. This biopolymer, produced by various microorganisms, offers several advantages, including rapid biodegradability, low toxicity, and a high degree of crystallinity. PHB is a thermoplastic polyester with relatively low permeability to oxygen, carbon dioxide, and water vapor positioning it as a strong option for applications in food packaging and biomedicine. The production of PHA has been explored through various biotechnological approaches, including the use of Gram-positive bacteria such as Bacillus, Rhodococcus, and Staphylococcus; Gram-negative bacteria such as Acinetobacter, Azotobactor, Burkholderia, Halomonas, Klebsiella, Pseudomonas, and Ralstonia; algae such as Arthrospira, Botryococcus, Chlamydomonas, Chlorella, Nostoc, and Spirulina; and engineered microorganisms such as Escherichia, Halomonas, Bacillus, and Saccharomyces have been reported to produce PHA (Patel *et al.,* 2021; Kalia *et al.,* 2024).Current global production of PHA, which includes PHB as one of its varieties, is approximately 100 tons annually and is projected to reach 500,000 tons per year by 2020, reflecting the increasing demand for eco-friendly materials (Kalia *et al.,* 2021; Broda *et al.,* 2024) . However, the widespread use of PHB is still limited. Overall, PHB's status is characterized by a mix of promising advancements and ongoing challenges. Its potential for sustainable and innovative applications continues to drive research and development efforts, aiming to overcome barriers and realize its full potential. Bioprocess development and metabolism of PHA from biowastes is presented in Figure 2.

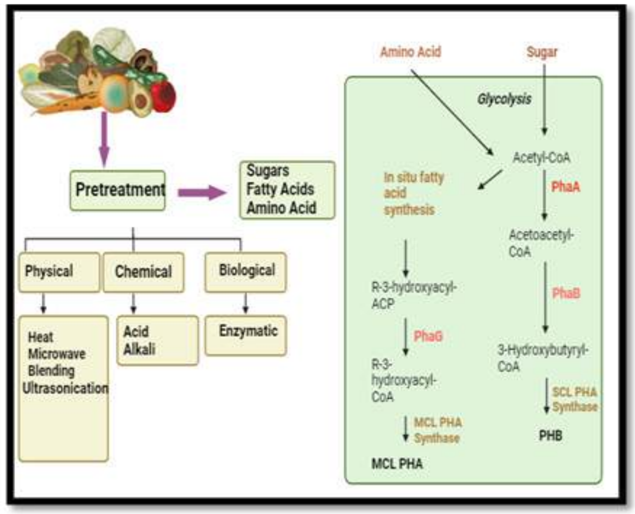

Fig. 2. Biowaste-derived sugars production and PHA metabolism.

CONCLUSION

Rising plastic production has intensified the problems of waste accumulation and microplastic pollution in ecosystems. Moving towards a circular economy can significantly reduce this burden by promoting recycling, reuse, and sustainable consumption. Biodegradable alternatives like PHAs, especially PHB, offer a promising solution with applications in packaging and biomedicine. Though challenges remain in large-scale production and cost efficiency, ongoing research continues to expand their potential. A coordinated global effort integrating innovation, policy, and consumer responsibility is essential to tackle the plastic menace sustainably.

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ENDING PLASTIC POLLUTION: A GLOBAL IMPERATIVE FOR A SUSTAINABLE FUTURE

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ABSTRACT

Plastic consumption continues to rise due to urbanization and increasing global demand. While the plastic production sector in India is experiencing significant growth, unscientific waste management practices are causing serious environmental harm. This situation highlights the urgent need for efficient planning and the integration of the "Design for Environment" concept, along with improved end-use applications and sustainable plastic waste management solutions.Studies on global plastic production and the resulting pollution have identified plastic waste as a significant environmental concern. The adverse effects of plastic waste on marine life, human health, and the broader environment have raised widespread public alarm, underscoring the urgent need to protect ecosystems and the species that rely on them.Thus eradicating Plastic Pollution is the necessity of the hour for a Sustainable Tomorrow.

Key words: Polymer, Circular Economy,Biodegradable,Recycling,Pyrolysis

THE DUAL CHALLENGE OF PLASTIC AND CLIMATE CHANGE

Plastic is a synthetic, organic polymer derived from fossil fuels, like petroleum and deeply penetrated in modern life since the plastics industry emerged as a major player in all sectors.With appealing characteristics including versatility, durability, flexibility, and low production cost plastics have become widespreadeverywhere with end-use application such as packaging, construction, and other consumer products.As a consequence, global plastic production has reached at an average of nearly 9% per year since 1950, far exceeding anyother industry (Chalmin,2019, Singh *et al.,* 2022). According to UNEP, more than 460 million metric tons of plastic are produced every year, with an average annual growth rate of 3.6%. The top three end users of Plastic products are Packaging,construction, and transportation sectors, accounting for about 31%, 16%, and 14% of total demand in 2019 (OCED,2022).

PLASTIC POLLUTION: THE SCALE OF THE PROBLEM

TPlastic pollution has become one of the most pressing environmental issues of our time, affecting ecosystems in every corner of the planet. A study by Ritchie *et al.,* (2023) found that plastic production has more than doubled over the past 20 years. Nearly 70% of global plastic pollution comes from just 20 countries, which make up only around 10% of the world's 195 nations (Lebreton *et al.,* 2018).Karali *et al.,* (2024) report that plastic production and disposal account for roughly 5% of global greenhouse gas emissions.

The World Economic Forum's 2021 report indicates that half of all plastic produced is discarded after a single use. Improper disposal of plastic waste not only pollutes and harms the environment, also becoming a widespread driver of biodiversity loss and ecosystem degradation. It poses risks to human health, compromises food and water safety, strains economic activities, and accelerates climate change. A 2022 OECD study found that around 91% of global plastic waste remains unrecycled and primarily originates from short-lived applications—those with lifespans under five years—such as packaging (40%), consumer products (12%), and textiles (11%).Additionally, a larger portion of plastic waste is mismanaged and ends up as litter (22%) compared to the amount that is collected for recycling (15%) (OECD, 2022). A study by the Nordic Council of Ministers and Systemiq (2023) reported that mismanaged plastic waste—waste that is not recycled but instead landfilled or incinerated—is projected to nearly double between 2019 and 2040.

Since plastic doesn't biodegrade, it gradually breaks down into microplastics—tiny particles that pollute the soil, water, and even the air we breathe. In 2019, microplastics (fragments larger than 5 mm) accounted for 88% of global plastic leakage into the environment—approximately 20 million metric tons—polluting ecosystems worldwide. Single-use items like bottles, caps, cigarette butts, shopping bags, cups, and straws are the leading sources of plastic pollution.Exposure to natural elements such as sunlight, wind, water currents, and other weathering processes causes plastic to degrade into microplastic particles (less than 5 mm) and nano plastic particles (smaller than 100 nm). Primary' microplastic particles are released from products like synthetic textiles and tires through abrasion. Nano plastics can penetrate cell membranes and enter living organisms. Microplastics have been detected in human blood, lungs, and even placentas, sparking concerns about their potential long-term health effects. Marine ecosystem is particularly vulnerable.Each day, over 2,000 garbage trucks worth of plastic end up in our oceans, rivers, and lakes (UN, 2023). Over 100,000 marine mammals die each year due to entanglement in or ingestion of plastic waste in the ocean (UNESCO, 2022).Sea turtles often confuse plastic bags for jellyfish, birds mistakenly feed plastic to their chicks, and whales have been found washed ashore with stomachs filled with plastic debris.The impacts are deeply tragic—and completely avoidable.Addressing plastic pollution begins with acknowledging its serious consequences. Equally important is raising awareness and promoting collective action toward sustainable solutions—an urgent priority for our time.

SOURCES AND SCOPE OF PLASTIC POLLUTION

Most pollution originates from land-based sources such as urban and stormwater runoff, littering, industrial activities, tire abrasion, construction, and agriculture. In marine settings, the majority of plastic pollution stems from land runoff, along with contributions from paint chips shed by ships, discarded fishing equipment, and other sources within the ocean. A further factor driving plastic pollution is the insufficient infrastructure and resources in many countries to properly handle plastic products and waste, often leaving local communities to bear the burden. Island nations, developing countries, Indigenous peoples, local communities, women, and children are among those most severely affected by the impacts. The issue is worsened by the global trade of plastic products and waste to regions lacking the infrastructure needed for safe and environmentally responsible management. Major contributor to plastic Pollution is-

- **Single-Use Plastics:** Products such as plastic bags, straws, bottles, and packaging are used for a short time but remain in the environment for hundreds of years. Around 85% of single-use plastic packaging ends up in landfills or as unmanaged waste (UNEP, 2023).
- **Microplastics:** These are small plastic particles formed either from the breakdown of larger plastic items or intentionally produced for use in products like cosmetics and textiles.
- **Industrial Waste:** Pollution also results from plastic production and industrial processes, including spills and poor waste management practices.

ENVIRONMENTAL IMPACT OF PLASTIC POLLUTION

Marine Ecosystems

- **Marine Wildlife:** Marine animals frequently ingest plastic debris, mistaking it for food, or become entangled in it, resulting in injuries, suffocation, or death. This impacts a wide range of species, including seabirds, turtles, whales, and fish.
- **Ecosystem Disruption:** Plastic pollution disturbs natural habitats and ecosystems, threatening biodiversity and disrupting marine food chains. For example, coral reefs are at risk due to being entangled in or smothered by plastic debris.
- Toxicity and Bioaccumulation:Plastics can release hazardous chemicals and absorb pollutants from seawater. These toxic substances accumulate in marine organisms, potentially endangering human health through the consumption of contaminated seafood.

Land and Air Pollution

- **Environmental Degradation:** On land, plastic waste pollutes landscapes, blocks waterways, and degrades soil quality. It can remain in the environment for centuries, harming natural ecosystems and affecting agricultural areas.
- **Airborne Microplastics:** Microplastics can travel through the air, reaching both remote and urban areas. This widespread distribution raises concerns about their potential effects on human health and ecosystems far from where they originated.

Global Implications and Long-Term Effects

- **Climate Change:** The entire lifecycle of plastics—from production to disposal—generates greenhouse gas emissions, intensifying climate change through activities like fossil fuel extraction and refining.
- **Economic Costs:** Plastic pollution places heavy financial strain on communities and industries, with costs related to cleanup efforts, healthcare, and negative effects on tourism and fisheries.

ADDRESSING THE CRISIS: SOLUTIONS AND PROGRESS

Plastics, a type of polymer, are widely used across the globe in both household and commercial environments. Their widespread use has led to a growing accumulation of plastic waste. To effectively combat plastic pollution, a systemic transformation is necessary. Addressing the risks associated with plastics demands coordinated efforts from various stakeholders (Jia *et al.,* 2019). The approach involves reducing the most problematic and unnecessary plastic usage, alongside three key market shifts: Reuse, Recycle, and Reorient and Diversify, as well as measures to address the existing plastic pollution legacy. Managing plastic waste is currently one of the most pressing global challenges. Recent efforts to tackle plastic waste have included road construction, recycling, incineration, mechanical processing, and recycling from recycled materials. Unlike other end-of-life treatments, this refers to reprocessing plastic waste to manufacture new products. "Feedstock recycling" specifically involves breaking down used plastics into smaller molecules that can be used as raw materials to produce new petrochemicals and polymers. Conversely, converting plastic waste into steam, heat, or electricity through combustion is known as energy recovery. Since plastics are mainly made from crude oil, they have a higher calorific value than many other materials, making them a significant source of energy. Although each method has its advantages and disadvantages, bioremediation stands out as the most cost-effective and environmentally friendly approach for managing plastic waste. The techniques involved include—

•**Reduce, Reuse, recycle:** Promoting responsible consumption habits and improving recycling infrastructure are essential steps to minimize plastic waste.

a) Mechanical Recycling

Mechanical recycling is the most widely used process for recycling plastics. This method includes sorting, cleaning, shredding, melting, and pelletizing plastic waste to create recycled plastic pellets or flakes. These pellets can then be utilized to produce new plastic items, which helps lower the need for virgin plastics and prevents plastic waste from ending up in landfills or being incinerated.

b) Chemical Recycling/Feedstock Recycling

Chemical recycling, sometimes called advanced or tertiary recycling, entails breaking plastic waste down into its chemical components or transforming it into liquid fuels through chemical reactions. Unlike mechanical recycling, which simply melts and reshapes plastics, chemical recycling breaks the polymer chains apart, allowing for the recycling of a wider variety of plastics, including mixed and contaminated types that are difficult to process mechanically. Recent progress in chemical recycling technologies encompasses methods such as pyrolysis, depolymerization, and gasification. For instance, pyrolysis involves heating plastic waste without oxygen to break it down into gases, oils, and char. These byproducts can be further refined and used as raw materials for producing new plastics, chemicals, or fuels. Depolymerization uses catalysts to chemically break down plastics into monomers, which can then be purified and repolymerized into high-quality plastics.

c) Biological Recycling (Biodegradation and Bioplastics)

Biological recycling utilizes biological agents—such as microorganisms, enzymes, or composting methods—to decompose plastic waste into natural substances like water, carbon dioxide, and biomass. This method is especially applicable to biodegradable plastics and certain compostable plastics engineered to break down in specific settings, such as industrial composting plants or marine environments.

Recent advancements in biological recycling technologies involve creating improved biodegradable plastics that break down more effectively across different environments. Research is aimed at enhancing degradation rates and end-of-life solutions for bioplastics, ensuring they decompose into harmless byproducts without leaving behind toxic residues or microplastics in the environment.

• **Value addition to Recycled material**

Technological advancements are making it possible to use recycled plastics in a broader variety of products, such as packaging, automotive components, construction materials, and consumer goods. Additionally, non-recyclable plastics are being utilized in applications like road construction, as fuel in cement kilns to generate heat, and in the production of pavement blocks.

a) Innovation and Policy: Promoting innovations in sustainable materials, enforcing extended producer responsibility (EPR) programs, and prohibiting single-use plastics can effectively reduce pollution at its origin.

b) International Cooperation: International cooperation is essential for addressing plastic pollution on a broad scale, with efforts such as the UN's Clean Seas Campaign promoting collaboration between governments, industries, and civil society.

c) Phasing out single-use plastics: Many countries have already introduced bans and restrictions on items such as straws, bags, and cutlery.

d) Improved waste management systems: Enhanced waste management systems are particularly crucial in developing countries, where infrastructure deficiencies often result in open dumping and uncontrolled plastic pollution in the environment.

• **Building materials**

Recently, there has been growing interest in substituting certain concrete components with solid waste. Developing environmentally friendly concrete is essential, as the primary binder in conventional concrete, Portland cement, generates significant carbon dioxide emissions during its production. Incorporating materials like plastic waste can enhance the mechanical properties of building materials by increasing their density and compressive strength. These properties include water absorption, slump flow, density, compressive and tensile strength, workability, unit weight, pulse velocity, air content, fire resistance, flowability, fresh and hardened densities, flexural strength, apparent porosity, drying behaviour, water retention, immersion water absorption, capillary water absorption, ultrasonic wave velocity, dynamic modulus of elasticity, visual assessment, and content weight.

PYROLYSIS OF PLASTIC WASTE

Pyrolysis, also referred to as "thermolysis," is a well-known technology used mostly to convert biomass into biofuels, biochemicals, and other biobased products (Wang *et al.,* 2020).In recent years, pyrolysis has increasingly been used to transform waste plastics into valuable products. Pyrolysis is the thermal breakdown of organic materials in low-oxygen or oxygen-free environments. It typically occurs at temperatures ranging from 350 to 700 °C (662 to 1,292 °F) (Li *et al.,* 2022). This process breaks down polymers into much shorter molecular chains or even monomers—the fundamental components used to produce plastics. Pyrolysis provides an eco-friendlier alternative to traditional landfilling for managing plastic waste. As a versatile thermochemical conversion method, it is widely adopted due to its ability to produce different valuable outputs based on operating conditions.

Pyrolysis offers a way to upcycle waste plastics by breaking them down into smaller molecules that can be reused to create new plastics and other valuable materials (Li *et al.,* 2022). Depending on the specific reaction conditions, the pyrolysis process yields products such as waxes, oils, gases, and char or ash (Zhao *et al.,* 2020). Among these, waxes and oils are the primary outputs and can be further processed into fuels, chemicals, or even the original types of plastics.

From the perspective of Circular economy, converting waste plastics into chemicals and new plastics is preferable. Additionally, pyrolysis oil can be integrated into existing virgin feedstock streams to manufacture plastic monomers, resulting in new plastics with properties identical to those made from conventional petroleum-based materials.

UNDERSTANDING THE NEED FOR ALTERNATIVES

Plastics are widely used across various industries due to their adaptability, strength, and low cost. However, their environmental impact—from marine pollution to threats to wildlife—emphasizes the need to seek alternative materials that offer similar performance with a lower ecological footprint.

PROMISING ALTERNATIVES TO TRADITIONAL PLASTICS

• **Bioplastics:** Derived from biomass sources such as corn starch, sugarcane, or algae, bioplastics offer a promising alternative to fossil fuel-based plastics. They have properties like biodegradable, compostable, or recyclable, depending on their composition.

• **Bio-based Plastics:** Unlike bioplastics, bio-based plastics are made from renewable biomass sources but are not always biodegradable. However, they can still help lower carbon emissions compared to traditional petroleum-based plastics.

• **Polylactic Acid (PLA):** PLA is a bioplastic produced from fermented plant sugars, typically derived from corn starch. It is compostable under certain controlled conditions and is widely used in applications such as packaging and food containers.

•**Biodegradable Plastics:** Biodegradable plastics are engineered to decompose faster than conventional plastics, breaking down through biological processes into natural substances such as water, carbon dioxide, and biomass.

• **Natural Fibers:** Natural materials like hemp, bamboo, and jute can serve as sustainable alternatives to plastic, offering durability and biodegradability for use in textiles, packaging, and construction.

• **Mycelium Packaging:** Packaging made from mycelium—the root structure of fungi—is becoming increasingly popular due to its biodegradability and versatility in being molded into different shapes.

CHALLENGES AND CONSIDERATIONS

• **Performance and Durability:** Alternatives need to equal or surpass traditional plastics in durability, barrier capabilities, and shelf life to guarantee practicality and gain consumer acceptance.

• **Cost and Scalability:** Economic feasibility continues to be a challenge for many alternatives, as scaling up production to satisfy global demand while staying cost-competitive with traditional plastics demands substantial investment and technological advancements.

• **End-of-Life Options:** Effective disposal and recycling systems for bioplastics and biodegradable plastics are crucial to realizing their environmental benefits. Composting facilities and recycling processes must be equipped to handle these materials properly.

CIRCULAR ECONOMY

Plastic plays a vital role in modern society, influencing industries ranging from agriculture to healthcare. The global plastics market is expected to grow to 754.3 billion US dollars by 2027 (Garside, 2020). Therefore, embracing a circular economy model—which emphasizes reintegrating all waste materials back into the production cycle—is crucial for promoting the sustainable development goal of responsible consumption and production. The UNEP and the European Union have collaborated to advocate for a circular economy model, which differs from the traditional linear economy that follows a one-way path from resource extraction to disposal. This linear system results in resource depletion and growing waste accumulation. In contrast, the circular economy promotes recycling products at the end of their life cycle, reducing waste, conserving resources, and keeping materials circulating within the economic system. Additionally, it can offer consumers durable, innovative products that save money and often enhance quality of life.

LOOKING AHED: A PLASTIC-FREE & SUSTAINABLE FUTURE

The environmental impacts of plastic pollution transcend national borders, requiring coordinated international efforts to tackle its far-reaching consequences. By raising awareness, enforcing effective policies, and embracing sustainable alternatives, we can safeguard our oceans, land, and communities from the damaging effects of plastic pollution. Eradicating plastic pollution is not an impossible dream—it is an achievable goal.Through coordinated global cooperation, technological innovation, and widespread changes in behaviour, we can transition to a circular economy where plastics are reused, repurposed, or eventually eliminated. As the world faces the growing challenges of plastic waste, recycling has taken on an increasingly important role. Progress in recycling technologies is essential for improving the efficiency, effectiveness, and sustainability of plastic waste management. These innovations encompass various techniques—from mechanical recycling to chemical processes—aimed at transforming plastic waste into valuable raw materials and reducing dependence on virgin plastics.

Stopping plastic pollution begins with bold decisions, responsible actions, and a shared dedication to safeguarding our planet. The search for effective plastic alternatives is an ongoing process fuelled by innovation, environmental consciousness, and supportive policies. While no single material can immediately replace traditional plastics, a combination of bioplastics, bio-based materials, and innovative packaging offers a hopeful way forward to reduce plastic pollution and advance sustainability. By embracing these alternatives and investing in advancements in material science and recycling infrastructure, we can collectively reduce our dependence on traditional plastics and lessen their environmental impact, paving the way for a healthier planet for future generations.

FROM NO PLASTIC TO KNOW PLASTICS

Plastics have emerged as a central issue in the global conversation on pollution and climate change.However, this perception often overlooks a crucial point that Plastics themselves aren't the problem—it's the improper use, mismanagement, and lack of effective recycling systems that lead to environmental harm.Rather than placing blame on plastics, we should recognize their essential role and focus on promoting responsible production, use, and disposal practices.

Plastics are vital to the healthcare industry due to their sterility, safety, and ease of disposal. Polymers like PVC, PP, and PE are widely used in the production of disposable syringes, IV and blood bags, catheters, tubes, PPE kits, face masks, and pharmaceutical blister packs. These materials ensure infection control, sterile storage, and single-use hygiene, all at an affordable cost. No alternative material matches this unique blend of properties—especially during pandemics and medical emergencies, when such advantages become indispensable.

Plastics are widely utilized in modern food packaging to maintain freshness and reduce spoilage. With food waste being a major global challenge, plastics contribute significantly by enabling smart packaging technologies. Multilayer barrier films—such as PET/PE/PA—offer excellent protection against oxygen and moisture, helping to extend shelf life and prevent spoilage during transport and storage. Additionally, access to clean drinking water and proper sanitation is a basic human right, and plastics play an essential role in delivering this through durable piping systems made from materials like HDPE, uPVC, CPVC, and PPR. Reinforced plastic tanks and joints provide durable, leak-proof, and corrosion-resistant solutions. Plastic piping systems are not only long-lasting—often exceeding 50 years—but also easy to install, making them ideal for both urban water infrastructure and rural programs like the Jal Jeevan Mission. In agriculture, plastics have revolutionized farming, especially in regions facing water scarcity. Technologies such as drip and sprinkler irrigation systems using PE and LDPE pipes, mulch films for soil conservation, greenhouse and tunnel covers, crop protection films, and silage bags have significantly boosted productivity. The integration of plastics into farming practices promotes climate-resilient and resource-efficient agriculture. The world doesn't need more blind bans or surface-level solutions. It needs a deeper understanding—a relationship with plastic that is responsible, respectful, and realistic. So instead of shouting "No Plastics" and walking away, let's engage, educate, and evolve the conversation. Because when we Know Plastic, we have the power to change the story—from one of pollution to one of possibility.

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INDIGENOUS SEED CONSERVATION PRACTICES IN THE TRANS-HIMALAYA: LESSONS FROM SPITI VALLEY

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ABSTRACT

PIndigenous seed systems developed over centuries have enabled farming communities to conserve locally adapted landraces, ensure food security, and sustain livelihoods. This article presents a case study of seed storage and exchange system practised by the farmers of Spiti Valley in the state of Himachal Pradesh. The farmers in Spiti follow traditional underground seed storage structures and barter-based seed exchange function as low-cost, climate-resilient alternatives to centralised seed banks. Strengthening indigenous, community-managed seed conservation practices in the Trans-Himalayan region offers effective pathways for conserving agro biodiversity, enhancing food security, and strengthening livelihood resilience, and should be formally integrated into government climate and agriculture programmes.

Key words: Agroecology; Trans-Himalayan; Indigenous seed; Seed bank; Naked Barly; Black Pea; Traditional Farming

BACKGROUND

The Trans-Himalayan region of India, located in the north of Great Himalayan range, is characterized by cold arid climate, high elevation and short growing season. This region represents a distinct socio-cultural landscape inhabited by agro-pastoral communities who have inherited tremendous knowledge on agriculture and animal husbandry since ages. Much of the land in the region is uncultivable due to nutrient poor soil, short growing season and scarcity of water for irrigation. Yet the area harbours distinct niche crops adapted for such climatic conditions and forms a unique agro ecological zone (Gupta *et al.,* 2024). Spiti Valley in the state of Himachal Pradesh represents such cold arid region, characterised by long, harsh winters, low and erratic precipitation. Here, agriculture is largely dependent on snow- or glacier-fed irrigation and limited to a single cropping season, making local communities highly vulnerable to climate variability and external shocks. Under these conditions, the farming communities of Spiti have developed several systems of conserving soil nutrients, agricultural crops and seeds of traditional crops. Some of the traditional crops conserved by the farmers in Spiti include landraces of barley, wheat, and pulses that are well adapted to cold, drought, and low-input environments. These traditional seeds are selected, stored, and exchanged using indigenous knowledge systems that prioritise yield stability, seed longevity, nutritional value, and resilience rather than short-term productivity (Montufar & Ayala, 2024; Behl *et al.,* 2025). Such practices have helped maintain crop diversity, soil health, and adaptive capacity in an otherwise marginal environment(Asiedu-Darko, 2014).

This article deals with key features of seed storage and conservation as practised by the farmers in Spiti Valley, Himachal Pradesh. It is based on the observations made in the area as part of ongoing project, entitled 'Agroecology, climate resilient farming and livelihood enhancement in border village of Indian Himalayan region', being implemented by IMI (Integrated Mountain Initiative), funded by NMHS (National Mission of Himalayan Studies).

AGROECOLOGY AND TRADITIONAL FARMING SYSTEMS OF SPITI VALLEY, HIMACHAL

Spiti,a sub-division of district Lahaul & Spiti in the state of Himachal Pradesh, is located in the Trans-Himalaya. The region is characterised varying topography, including wide and extensive valleys, steep slopes with loose scree and exposed rocks, an undulating plateau and glaciers (Fig. 1). The valley aligned in north-west to south-east direction with altitude ranging between 3000 - over 6000 m asl. This region is flanked by the Great Himalayan range on the south, Barasigri group of glaciers on the west, Zanskar range in the north and Tibetan plateau on the northeast. Agriculture is practices only in the valleys and in some flat areas of the plateau. Agricultural activities are restricted to a single short growing season (May to August) and depend largely on snow- and glacier-fed irrigation systems, locally managed through traditional kuhlchannels. Despite these constraints, the farmers have

Fig. 1: Traditional agroecological landscape of Hikkim, Spiti Valley, Himachal Pradesh, showing high-altitude villages and irrigated fields sustained by snow- and glacier-fed kulh systems amid the Trans-Himalayan cold desert terrain.

evolved fairly stable agro ecological practices that emphasise stability, resource efficiency, and risk minimisation rather than high-input productivity. The traditional farming system of Spiti is deeply rooted in agro biodiversity adapted to high-altitude conditions, with traditional seed storage and conservation practices firmly embedded in the socio-cultural fabric of local communities. Non-monetary seed exchange systems based on trust and reciprocity ensure equitable access to quality seeds, particularly during crop failure, seed loss, or food scarcity. Women play a central role in seed selection, storage, and exchange, reinforcing household food security and intergenerational knowledge transfer. In the context of increasing climate uncertainty and market dependency, strengthening indigenous seed systems is essential for safeguarding agro biodiversity, enhancing food sovereignty, and supporting sustainable livelihoods in the Trans-Himalayan cold arid region.

Farmers cultivate a limited yet resilient set of indigenous crops, including multiple landraces of barley (*Hordeum vulgare*), naked barley (*Hordeum vulgare* var. *nudum*), wheat (*Triticum aestivum*), black pea (*Pisum arvense*), green pea (*Pisum sativum*) and potato (*Solanum tuberosum*) majorly, which are well suited to cold, drought-prone, and low-input environments (Fig. 2). These crops are grown under a traditional rotation system during the single Kharif growing season, in which barley and wheat are commonly rotated with black pea and green pea to maintain soil fertility and

Fig. 2: Traditional crops of Spiti Valley, Black pea (*Pisum arvense*) and naked barley (*Hordeum vulgare* var. *nudum*) grown under a high-altitude, single-season farming system in Lossar, Spiti Valley, Himachal Pradesh.

ensure stable production. This practise plays a central role in sustaining food and nutritional security in Spiti Valley. Indigenous crop varieties provide staple food, fodder, and crop residues that support integrated crop-livestock systems. The continued use of locally adapted landraces helps farming households buffer against climatic variability, crop failure, and market fluctuations. Traditional farming systems also support cultural continuity, indigenous knowledge transmission, and community-based resource management. Overall, the agro ecology and traditional farming systems of Spiti Valley represent a finely balanced interaction between climate, ecology, and human adaptation.

INDIGENOUS INFRASTRUCTURE FOR SEED STORAGE: THE KAKTI SEED CONSERVATION CAVE OF SPITI

Farmers in Spiti follow a careful approach to seed selection and storage, giving priority to grain quality, yield stability, and by-product value. Seeds are selected from solo crop fields to minimise contamination and ensure genetic purity. Exchange of seeds generally occurs when productivity begins to decline, typically after seven to eight years of continuous cultivation. During seed exchange, an additional quantity, usually around 25 per cent,is collected to compensate for storage losses and sowing wastage. Women play a central role in managing seed exchange, particularly for cereal crops, both within and across villages. A defining feature of Spiti's indigenous seed system is the use of traditional underground seed storage structures locally known as *Phanh*. Constructed entirely from mud and stone, these caves and underground bunkers provide natural insulation and protection from rodents, pests, moisture, and extreme temperature fluctuations without chemical preservatives.

One notable example of indigenous seed storage in Spiti, Kakti village of Kaza Panchayat, at an altitude of approximately 4,200 metres above sea level. This traditional seed storage cave has been carefully maintained by Mr. Chhering Namgyal, the fifth-generation custodian of the structure, reflecting an unbroken lineage of indigenous knowledge and stewardship spanning nearly four centuries. The seed storage has been practised for nearly 400 years and remains functional in villages. Originally used as a dwelling by his forefathers, the cave has gradually evolved into a dedicated space for seed storage and conservation, demonstrating adaptive reuse of traditional architecture. The cave contains two underground bunkers constructed entirely from locally available materials such as stone and mud (Fig. 3). These bunkers together have a storage capacity of approximately 400–500 kg and provide a naturally regulated microclimate that protects seeds from extreme cold, moisture fluctuations, rodents, and insect infestation. The stable underground conditions allow long-term storage without the use of chemical preservatives or modern energy-dependent technologies. The structure is used to preserve indigenous landraces of barley (*Hordeum vulgare*), including Soha barley and Kniu

Fig. 3: Custodian of a traditional seed storage cave (Phanh) at Kakti village, Spiti Valley, showing the exterior stone-built structure and the interior underground bunker used for conserving indigenous seeds.

(naked barley), as well as traditional landraces of black pea (*Pisum arvense*). The continued use of this seed storage cave illustrates the technical efficiency, durability, and ecological appropriateness of indigenous seed conservation systems. Beyond its functional role, the structure represents cultural continuity, intergenerational knowledge transmission, and community-based stewardship of agro biodiversity in the Trans-Himalayan cold arid.

INDIGENOUS SEED BANKS VS MODERN SEED BANKS: FUTURE PROSPECTS

As the farmers of Spiti are struggling to maintain age-old farming systems under changing climate and rush for cash crops, there is a need to revamp the system of conserving the quality seeds, exchange of seeds of traditional crops and establishment of modern seed banks. Modern seed banks are typically centralised and technology-driven, relying on controlled temperature and humidity for long-term conservation. While effective for genetic preservation, such systems are capital-intensive, energy-dependent, and geographically distant from farming communities, limiting their immediate usefulness in remote high-altitude regions. Indigenous seed banks, in contrast, are decentralised, community-managed systems embedded within local landscapes and livelihoods. Traditional seed storage structures, such asunder ground *Phanh* bunkers, maintain stable microclimatic conditions without external energy inputs. These systems function as dynamic, living seed systems where seeds are continuously cultivated, exchanged, renewed, and adapted, ensuring availability during climatic shocks, crop failure, or market disruptions. From a policy perspective, indigenous seed banks offer greater relevance for food security, seed sovereignty, and livelihood resilience in high-altitude regions. Integrating basic scientific documentation and quality control into indigenous systems can create hybrid models that combine conservation efficiency with local adaptability. This will enhance climate resilience, reduce dependency on external seed markets, and strengthen sustainable livelihoods. Strengthening indigenous seed banks directly contributes to India's commitments under the Sustainable Development Goals (SDGs 2, 12, 13, and 15), the National Biodiversity Action Plan (NBAP), and the National Action Plan on Climate Change (NAPCC), particularly the National Mission for Sustaining the Himalayan Ecosystem (NMSHE) and the National Mission for Sustainable Agriculture (NMSA).

CONCLUSION

Conservation and storage of quality seeds of traditional crops is an essential component of farming system in any agro-ecological zone. Indigenous and community-managed seed storage system as practised by the farmers in Spiti underlines the need for encouraging such practices with modern tools and techniques of seed preservation. Given the unique agro ecological conditions of high-altitude cold arid areas, indigenous seed conservation practices provide locally adapted solutions that are not adequately addressed by centralised systems. There is a need to strengthen the system of indigenous seed storage and exchange among the farmers under the border area development programme of the Government of India. Targeted financial and technical support should be extended for strengthening traditional seed storage infrastructure such as underground bunkers and stone–mud structures.

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POLLUTION IN RIVER GANGA; CONSEQUENTIAL HUMAN HEALTH HAZARDS AND THE PROMISES FROM HERBAL WORLD

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ABSTRACT

This research manuscript endeavours to analyse and critically evaluate the prevailing global situation of diarrhoea. The etiology of disease and its prevalence and dominance in India, Uttarakhand and particularly in the holy city of Rishikesh, one of the most favoured tourist destinations in the world and the International Capital of Yoga have attracted ample attention. Further, the causes of increase in diarrhoea, its associated fatalities, damages in all spheres of life, historical analysis, types, severity, vulnerable effects on sufferers, cure and clinical management- related aspects etc., have also emerged as issues of paramount deliberation. It has further been ventured to evaluate the success and inherent side effects and traumatizing manifestations of modern synthetic drugs including antibiotics with regard to diarrhoea. On the basis of these observations and realizations, it was decided to move for newer, safer and better therapy. The natural and Traditional System of Healthcare and clinical management—Ayurvedic natural therapy—and its various merits and demerits were analysed at length. Ultimately, the intensive research analysis carried out here infers that a comprehensive research and development programme on Ayurvedic Herbal Drugs must be started and geared up as the top most priority research program, both at national and international levels, to ensure the availability of the better futuristic drugs of choice for disease free and quality life to the people across the world. The findings of this research study conclude that rationalizing, strategizing and scientifically developing better futuristic drugs of choice for the welfare of mankind, applying several recent biomedical tools and techniques, is the dire and emergent need of the hour with utmost significance.

Key words: Ganga water pollution, human interferences, disastrous health effects, herbs as effective remedies, Herbal immunology

INTRODUCTION

Ganga is a spiritual lifeline river for more than billions of people as they depend on her for all aspects of daily life, from drinking water to farming to moksha, spiritual and cultural heritage, but it is now under the full grip of serious pollution crisis. Sadly, the lust and greed of people have literally transformed it as a dumping yard and reservoir for industrial discharges, untreated household sewage, and agricultural runoff. Further, it is so because of the flowing routes this river passes through densely populated and industrialized areas, resulting in dangerous high pollution levels. In addition to the endangered aquatic species, this contamination puts the health of associated communities at serious risks that rely on this river for agriculture, drinking and bathing purposes. The domestic household wastes, municipal sewage sludge etc., containing nearly all types of pathogenic coliform bacteria, are considered as the biggest cause of about 80% pollution to river Ganga. Notably, about 15% of Ganga pollution is due to industrial effluents and the remaining 5% is attributed to non-point sources such as agricultural runoff and rural households (Dhiman *et al.,* 2014). The majority of Ganga pollution is organic waste, sewage, trash, food and human and animal remains. River Ganga is badly polluted in lower stretches and hence, it is ironically called the journey of pollution from Haridwar onwards to the bay of Bengal (Tripathi, 2020). Further, approximately 90 cities of various sizes and thousands of villages are located along the sides of Ganga in its closest vicinity and nearly all of their sewage/ wastes, over 1.3 billion litres per day, directly get drained into the river along with thousands of animal carcasses including mainly of cattle's (Bhutiani *et al.,* 2016). Some of the prominent cities, like Kanpur, discharge nearly 259 MLD of waste; Varanasi, nearly 250 MLD of waste; Patna, about 150 MLD of waste and West Bengal, nearly 700 MLD of wastes. Surprisingly, nearly 45 MLD of untreated wastewater from 234 cities is discharged in Ganga and 142 industries in Uttar

Pradesh add approximately 260 million litres of industrial effluents/wastes in Ganga/day (Dhiman *et al.,* 2014). Mishra *et al.,* (2009) reported that total coliform counts in Ganga at Varanasi ranged from 20,900 to 25,400 MPN/100 ml and faecal coliform counts were 93/100 ml. These values are substantially higher than the permissible limits set by ISI and WHO. It was stated in 2012, during the meeting of Ganga Basin Authority, that every day 29,000 trillion litres of wastes, dirty and polluted water and industrial effluents are drained in the river Ganga in its journey of nearly 2525 kilometres from Gangotri to the bay of Bengal (Dwivedi *et al.,* 2018). Domestic and industrial wastewater constitute a constant pollution source, whereas surface runoff is a seasonal incidence of pollution controlled mainly by the climate (Singh *et al.,* 2004).

METHODOLOGY OF STUDY PLAN

This review research article was prepared by collecting and scanning the information from many literature sources using several search engines like internet sources, Google Scholar, Web of Science, Google chrome, Research Gate, PubMed, Scopus etc. Further, peer-reviewed papers, clinical trials and original research articles from the relevant fields were included for literature work. For ensuring the quality and relevance of the manuscript, articles were first filtered based on their title and abstract and subsequently being evaluated in totality.

POLLUTION IMPACTS ON HUMAN HEALTH AND DANGERS FOR SURVIVAL

Pollution is identified as a complication caused by contamination and alteration to the natural composition. Its causation is directly related to the degree of unlawful and unethical activities of human beings to the environment (UNEP, 2021). This problem may easily be envisaged as exactly opposite happenings to the normal established laws of nature defying the natural system by breaking the healthy, smooth and congenial relationships of nature with its dearer living beings including the human beings (Warde *et al.,* 2018). The existence and continuance of pollution, however at much below the level of detection and tolerance, is known to be older than even the dawn of human civilization (Pyne, 2001). The explosion in human population especially during the preceding four-five decades coupled with more and more needs for the procurement of food, clothing and shelter together further fueled the process of rapid industrialization, the ever increasing use of chemicals, fertilizers and the pesticides in agriculture for ample and good quality food grains, deforestation, urbanization, ultra modernization, etc. (United Nations, 2019; Singh, 2006; Pilon-Smits, 2005). The ill consequences of issues, under discussion, caused an exorbitant dumping and subsequent assemblage of pollutants to our neat and habitable natural environment and thus exceeding gradually far more than the tolerance limit which ultimately red signalled and warned the entire global human community to recognize pollution, particularly the environmental pollution as serious and dreaded threat for even our very survival (Health Effects Institute, 2022; WHO, 2022; CPCB, 2023). The need and importance of these issues forced to establish separate departments in higher academic centres like Universities, Colleges as a new discipline-Environmental Science for studying various aspects of environmental pollution, contamination and several rescue/ remedial measures (Carson, 1962; Warde *et al.,* 2018). Further, several national and state level research funding agencies have been made for effective and fruitful study and research achievements (D'Souza, 2001; UNEP, 2021). Pollution, encompassing air, water, soil and chemical contaminants, represents one of the most pressing threats to human health and survival worldwide. According to the World Health Organization (Schell *et al.,* 2006), ambient air pollution caused an estimated 7 million premature deaths annually, primarily from cardiovascular diseases, respiratory infections, stroke and lung cancer. Fine particulate matter (PM 2.5), nitrogen oxides, sulphur dioxide and ground level ozone contribute significantly to these health clinical reflections by penetrating deep into the lungs and bloodstream, causing inflammation and impairing organ function. In low- and middle-income countries, such as India, the impact is even more severe. Further, the Global Burden of Disease (GBD) study reported that air pollution accounted for more than 2 million deaths in India alone in 2019 (Health Effect Institute, 2022). Urban areas like Delhi frequently experience hazardous air quality index (AQI) level that crosses safe limits for extended periods, resulting in causation of the increased rates of asthma, chronic obstructive pulmonary disease (COPD), and acute respiratory infections, particularly among vulnerable groups like children and the elderly people (CPCB, 2023). Beyond air pollution, water contamination with heavy metals, pesticides and pathogens poses significant risks to human health, including gastrointestinal diseases, neurological disorders and developmental impairments (WHO, 2017). Soil pollution further exacerbates these risks by introducing toxic substances into the food chain, impacting nutrition and leading to bioaccumulation of harmful compounds in humans (UNEP, 2021). Deliberating on these issues of extreme complexities urgently demand for amicable and innovative solutions. In such a grim situation, biotechnology suitably offers powerful tools for pollution remediation and monitoring thereby helping to protect human health. Techniques such as phytoremediation, using genetically engineered plants to extract and detoxify pollutants from soil and water, have been successfully applied to remediate contaminated sites and reduce the exposure to risks (Pilon-Smits, 2005). Similarly, myco-remediation employs fungi capable of decomposing complex organic pollutants and heavy metals thereby providing eco-friendly and cost-effective remediation options (Singh, 2006). Moreover, advances in molecular biotechnology have enabled the development of biosensors which are capable for real time detection of environmental toxins and facilitate early intervention and prevention of pollution related diseases (D'Souza, 2001). Through these integrated biotechnological strategies, it is possible not only to mitigate pollution but also to promote ecosystem restoration and sustainable health to human beings. The world scenario of studying and conducting research in the area of environmental pollution, for evolving suitable measures and devising strategies as to how this famine can be contained and destroyed, has changed drastically for fruitful results to achieve. All these new insights and closure look to this science made it even more exciting, rewarding and fascinating throughout the world. It further resulted in establishing so many meaningful branches of which Environmental Biotechnology is likely to occupy the central position of attention because of its vast, valuable and feasible applications to abate the pollution and problems caused as a result of its ill consequences. The anticipated menace peeping further proves even more fatal and disastrous for life. The anthropogenic sources of pollution are held most accountable for posing serious challenges, always thereby destabilizing the healthy and congenial relationships between the biotic and abiotic components of the ecosystem. The grim and noxiousness of pollution being realized and faced in the form of acid rain, Minamata disease in Japan, global warming, Bhopal gas tragedy in India, greenhouse effect, exposure to ultraviolet radiation causing cancer and other dreaded diseases, ozone depletion and ozone hole, toxicity, suppression/destruction to the host disease resistance power (immunity), spurt of various killer diseases etc. are looming large over the planet earth and committed to diminish the life including human beings thereby deserting and converting it as a crematorium. The multi-faceted attacks of environmental pollution by intoxicating the three prominent components of the ecosystem- water, soil and air, is again a big uphill task to combat and control this environmental crisis. Furthermore, the ill consequences of pollution as fatalities, calamities and physical and mental debalities and disabilities will have to be considered seriously and tackled judiciously and rationally with genuine scientific skills for peaceful survival in a healthy, conducive, prosperous, habitable and clean environment with pleasure to make sustainable developments ahead of us for coming generations. Nearly 79% of earth is occupied by water and interestingly the freshwater used for drinking and irrigation purposes is represented by lakes, rivers, fountains, ponds etc. constituting only 2% of it. Thus, it can be well realized that pollution has really posed serious threats including our very survival in the form of causing dreaded and clinically unmanageable diseases by modern synthetic drugs and allopathy. Pollution affects both the abiotic and biotic components of the ecosystem thereby destabilizing the healthy and congenial relationships of living beings with the environment. Diseases are one of such types of problems caused due to environmental pollution. Biological water quality is adversely affected by various types of contamination, lack of sanitation, upstream activities and transport and in house contamination and consequently poses threatening and damaging effects up to 95% in the form of several severe and fatal water borne diseases like gastroenteritis, conjunctivitis, encephalitis, dermatitis, giardiasis, amoebiaosis, colitis, diarrhoea of several types like bacterial, viral and protozoan, malaria etc. Mainly the bacterial diarrhea including Salmonella; E. coli; Pseudomonas are being transmitted through contaminated water and prevalent in developing countries with poorer hygienic conditions and low socioeconomic status. Close proximity of drinking, bathing, sewage, washing etc. are envisaged as the main precipitating factor for such diseases. An estimated 80% of all health problems and 1/3rd of deaths in India are attributable to water borne diseases (Air pollution rising in Kanpur CSE BS Reporter/New Delhi Dec 8, 2009). It is an established truth that good water quality produces healthier humans than one with poor water quality.

GANGA POLLUTION AND HUMAN HEALTH

Industrial effluents and sewage/domestic wastes entering the water bodies are among the main sources of environmental toxicity damaging and destroying the aquatic biota and deteriorating the water quality (Tripathi, 1993; Sinha and Paul, 2014; Sinha *et al.,* 2016). The heavy metals' caused river water pollution, in terms of toxicity, is one of the serious threats posed in most of the metropolitan cities of India and other developing countries. These heavy metals are of serious concern due to not being readily degradable and accumulating in the animal as well as human bodies through the food chain, causing serious environmental problems (Parveena *et al.,* 2010). Heavy metals in water systems are hazardous to human health, including developmental retardations, nephrological complications, cardiac troubles, various cancers and even deaths (Paul, 2017). Major pollutants found in water include volatile, biodegradable and recalcitrant organic compounds, toxic metals, plant nutrients, suspended solids, microbial pathogens and the parasites (Bitton, 1994, Sinha and Paul, 2016). Exposure to heavy metals caused profound deleterious effects on the immune system, including structural damage to lymphoid organs and significant impairment of both humoral and cell-mediated immune responses. In fish models, chronic exposure to contaminants has led to histopathological alterations in lymphoid tissues and disrupted leukocyte function, demonstrating broader ecological and health impacts (Weeks *et al.,* 1986; Tripathi, 1993; Khangarot *et al.,* 1999). Additionally, ongoing discharge of industrial waste and untreated domestic sewage into aquatic ecosystems has been shown to continuously elevate heavy metal concentrations in river water (Kapoor & Singh, 2021). The faunal diversity of river Ganga was surveyed extensively from Haridwar to Farakka (1663 Km) and 87 species of zooplankton, 83 species of fishes were observed (Sinha and Paul, 2014).

CLINICAL APPLICATION OF GANGA WATER

Water has been used, from time immemorial, for remedial and curative purposes. The river Ganga water has wide medicinal uses in local therapy. Further, outbreaks of acute diarrheal disease have been identified as causes of fatal disease dating back as far as the Sanskrit literature and during Hippocratic times (Singh *et al.,* 2011). Hippocrates, going back to 500 BC, described the healing of disease with Ganga water and observed the curative effect of Ganga water bath in the treatment of leprosy. Thus, the world credits Ganges water for the discovery of bacteriophages. Though invisible, it was possible to show that this principle of healing was due to particulates- and D'Herelle called these objects as bacteriophage (D'Hérelle, 2007). Overuse in human medicine and for agricultural purposes has become a recognized medical problem and scientists have become increasingly concerned about the occurrence of antibacterial resistance in the environment (Voudouris *et al.,* 2023). The most unfortunate part of this curative and therapeutic role played by Ganga water in the present-day scenario is refuted and wildly negated by the famine of water pollution. The scientific research-based observations on curative and clinical effects of Ganga water are all about one hundred year old when Ganga was pure enough with all divine features and pollution was not even in the stage of inception (Dwivedi *et al.,* 2018). We have to leave no stones unturned for restoration of Ganga health by making it free from the pollution menace if we desire to enjoy the clinical applications and curative relevance of Ganga for ourselves and associated communities. Due to the very high concentration of naturally occurring bacteriophages and antimicrobial minerals, which give its waters exceptional antibacterial features, the Ganga river has attracted scientific attention for its possible medicinal uses (Mishra & Nath, 2020; Koshy, 2019). The existence of phages capable of lysing multidrug-resistant bacteria including *Acinetobacter baumannii, Pseudomonas aeruginosa* and *Escherichia coli*, isolated from clinical samples in India, has now been verified by numerous workers (Sharma, Kaur & Mehta, 2022; Yadav *et al.,* 2022). The discovery of phages that are effective against drug-resistant *Pseudomonas aeruginosa* has also led to the discovery of novel lytic processes and genetic features that will aid in the development of future therapeutics with special name as phage therapy (Rathor *et al.,* 2022). In addition to in vitro results, a clinical case series that employed phage-rich Ganga water to treat persistent psoriasis reported significant improvements following at least four weeks of regular oral administration, indicating a potential dermatological use (Waghralkar & Jhunjhunwala, 2021). Its traditional usage in skin health has been supported by encouraging observational clinical data suggesting the extended oral intake of Ganga water containing phages can reduce the symptoms of chronic dermatological disorders including psoriasis (Waghralkar & Jhunjhunwala, 2021). These results highlight the potential of Ganga as a naturally occurring supply of biotherapeutic chemicals that can fight illnesses resistant to antibiotics. However, tackling environmental contamination including untreated sewage and industrial discharge- poses a threat that could neutralise these advantageous impacts of river on human beings. Further, developing standardized techniques for purification, phage isolation and safety are essential for sustainable clinical deployment (Voudouris *et al.,* 2023).

POLLUTED GANGA WATER AND ITS DISASTROUS EFFECTS ON HUMAN HEALTH

Water plays crucial roles in transmission of many infections and diseases. Water borne diseases become more panic and severe when water bodies get densely contaminated and polluted. Approximately 85% pollution in Ganga is due to domestic wastes. The water samples collected from Ganga in Varanasi revealed the fecal coliform counts of about 50,000 CFU/ 100 ml of water which is 10,000% higher than the government standard for safe river bathing. The aforesaid problems of pollution may be envisaged in the form of aetiological factors responsible for causing an array of water borne diseases including cholera, hepatitis, typhoid and amoebic dysentery. Nearly 90% human diseases are water borne. Malaria and other mosquito transmitted diseases like dengue, yellow fever, filariasis are water quality dependent. Malaria alone is responsible for greater morbidity and mortality than any other tropical disease. Further, high humidity and stagnant water are accountable for about 2 billion people being exposed to this disease and nearly 25% of children deaths. The spurt of diseases like tuberculosis, polio, hepatomegaly, hepatitis, liver cirrhosis, malaria, arthritis, nephritis, goitre, conjunctivitis and neuropathies has been observed and many of which have direct or indirect connections with unsafe water (Schell *et al.,* 2006 ; CDC, 2022). Modern biomedical research reveals that nearly 80–95% of communicable diseases in developing countries are waterborne or water-related, either due to pathogens or toxic chemical contaminants (WHO, 2022; Gleick, 2002). These contaminants induce physiological toxicity and immunological debilitation, potentially predisposing individuals to systemic failures comparable to those seen in the pathophysiology of AIDS/HIV, where the immune system is critically compromised (Chen *et al.,* 2009; Paul, 2018). We must, henceforth, anticipate unimaginable casualties, disasters and fatalities globally due to water pollution, especially when less than 2% of total water resources are freshwater sources usable for drinking purposes, yet are already causing significant health crises (UN-Water, 2021). Voluminous literature supports the afore stated facts, underscoring the urgent need for global water safety measures and environmental policy reforms.

AYURVEDIC HERBAL DRUGS PROMISING FOR A BETTER HUMAN HEALTH

Regardless of the wonderful, amazing and miraculous properties of allopathic drugs, in combating the diseases and containing the infections thereby extending the life span and enhancing vitality of human beings, their inherent complications, due to active component of drug development principle based on reductionism approach, of serious side toxic effects, drug resistance, withdrawal effects, recurrence of infections and diseases, immunosuppressive/ immune destructive effects, cost factor and unavailability in far flung areas etc., hinder the prompt, frequent, rational and judicious uses in cases of human ailments. It eventually forced us to look for an Alternative Therapy- The Ayurvedic Herbal Drugs, known as the best gift of Mother Nature, being free from the traumatizing complications of synthetic drugs. Further, Pro to body concept of action, holistic approach, principle of totality, eco-biofriendly innocuous nature, easy availability etc., are added values of relevance associated with these Natural Ayurvedic Herbal drugs – the safe alternatives to allopathic drugs. However, these drugs of amazing and wonderful properties lack reproducibility, clinical validity, credibility and hence the acceptability. It was urgently realized to apply Biotechnological techniques and tools for crediting them to be the futuristic drugs of choice for global benefits and well-being of mankind by way of their modernized promotion. More than three decades of immense research contributions in this area, we have reached to a conclusion that rasayana class of therapy i.e. the therapy of rejuvenations, immune facilitations and revitalizations. Pippali Rasayana, Bramhi, Ashwgandha, Sarpgandha, Pushkar mool, Tulsi, Neem etc. are some of the time-tested herbal remedies for offering disease free and better life to human beings. Clinical trials- both Single blind placebo controlled and double blind placebo controlled, were carried out and promising results with profound degree of clinical improvements had been recorded (Shinde and Kuchewar, 2021). The findings of our comprehensive research on several ayurvedic herbal drugs, applying various modern biotechnological and biomedical parameters like immunological, biochemical, pathological and clinical including single blind and double blind placebo controlled clinical trials, proved these drugs working mainly as immuno facilitators, rejuvenators, revitalizers in cases of human immunocompromised diseases including diarrhoeal diseases (Agrawal *et al.,* 1997). *Holarrhena antidysenterica* (Kutaja), *Aegle marmelos* (Bael), *Punica granatum* (pomegranate), *Berberis aristata* (Daruharidra), *Terminalia chebula* (Haritaki), *Emblica officinalis* (Amla) and *Glycyrrhiza glabra* (liquorice) are common ayurvedic medicines for bacterial diarrhoea. It has been demonstrated that these herbs have antibacterial, astringent and antidiarrheal qualities. These also stabilise the intestinal secretions, decrease motility and prevent the growth of Salmonella, Shigella and E. coli. In animal trials, the ethanolic extract of *Holarrhena antidysenterica* seeds successfully reduces clinical symptoms and regulates diarrhea (Sharma *et al.,* 2015). The fruit pulp of Aegle marmelos has bacteriostatic effects and decreases intestinal motility, demonstrating its strong antibacterial activity against enteric infections. Extracts from Punica granatum have antibacterial properties that work against a variety of bacterial types, including those that cause foodborne illnesses (Suresh *et al.,* 2009; Srivastava and Mondal, 2016). Berberine may be used to treat bacterial diarrhea since it has been demonstrated to change bacterial DNA replication and prevent the generation of enterotoxins (Sack and Froehlich, 1982). Due to its antibacterial qualities, Terminalia chebula has long been used to treat gastrointestinal issues, including diarrhea. Emblica officinalis is used to treat bacterial diarrhea because it strengthens the immune system and has antibacterial activity against a variety of infections (Tiwari and Barooah, 2024). Particularly in areas where antibiotic resistance is becoming a greater problem, incorporating these ayurvedic botanicals into treatment plans may offer efficient management choices. An intensified and composite scientific research plan was henceforth executed and our research findings provided sound basis to reproducibility and credibility of results and finally the global acceptability to these futuristic drugs of choice. Clinical standardization, reproducibility and credibility of results and finally the global acceptability to these futuristic drugs of choice are issues of extreme importance which need to be addressed on top priority by establishing the most exciting new discipline- Herbal Immunology.

CONCLUDING REMARKS

The present research article deals with the findings of the preceding analysis specially focusing on discernible impacts of pollutants on human health and the environment. River Ganga, revered as a lifeline for billions, now grapples with severe pollution challenges due to uncontrolled discharges from industry, domestic regions, agricultural runoff and religious activities. This environmental degradation has far reaching consequences, directly affecting the health of populations dependent on its waters and indirectly also the living beings. An array of waterborne and chronic diseases—ranging from gastrointestinal infections to carcinogenic effects—underscore the urgent need for sustainable remediation strategies to mitigate and neutralise the pollution crisis of Ganga. Amidst these challenges, the herbal world sufficiently appears to offer promising avenues for both detoxification and therapeutic support. Phytoremediation using selected plant species, along with herbal medicines for disease management, typifies nature's potential to counter balance anthropogenic harms posed. However, realizing this promise requires an integrated effort between traditional knowledge and modern science by strict implementation of robust policy measures. Conservation and restoration of life saving and divine river Ganga is not only an environmental imperative but also a public health priority and a cultural responsibility.

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HIMALAYAN ECOLOGY

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