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REVIEW

Impact of Urbanization on Biodiversity in the Global Biodiversity Hotspot of Sikkim Himalaya, India: A Review

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ABSTRACT

Sikkim, located in the Eastern Himalayan Region, represents one of the 36 globally recognized biodiversity hotspots and harbors an exceptional range of ecosystems within a relatively small geographic area. Over the past few decades, the region has witnessed rapid urbanization alongside other developmental activities such as hydropower construction, road expansion, mining and infrastructure development. While these processes have contributed to socio-economic development, they have simultaneously exerted significant pressure on the fragile mountain environment. This review examines the impacts of urbanization on biodiversity in the Sikkim Himalaya drawing attention to the ways in which land-use change due to urbanization, habitat fragmentation and economic development have altered ecological dynamics and threatened biodiversity of this region. The findings of the current study suggest that unplanned urban growth has led to the degradation of forest cover, disruption of ecological corridors thereby diminishing ecosystem resilience of the region. In addition, the current study highlights the challenges of balancing developmental imperatives with environmental conservation in the study area where both ecological integrity and human livelihoods are intricately interdependent. This study highlights the urgent need for integrated land-use planning that incorporates ecological corridors, urban green spaces, and community-based conservation to mitigate biodiversity loss. Strengthened

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governance, sustainable tourism, invasive species control, and systematic biodiversity monitoring are essential to balance urban development with ecological integrity. Most importantly, holistic and interdisciplinary approaches are critical to ensuring that urban growth in the Global Biodiversity Hotspot of the Sikkim Himalaya aligns with global biodiversity conservation goals and the Sustainable Development Goals (SDGs).

Keywords: Urbanization; Biodiversity Conservation; Biodiversity Hotspots; Sustainable Development; Eastern Himalaya; Sikkim Himalaya

1. Introduction

Urbanization is a process that transforms natural ecosystems and landscapes into man-made systems [1,2]. This phenomenon has emerged as a major global trend over the past few centuries, carrying substantial social, economic, and environmental implications [3,4]. It is a defining feature of modern societal development [5] and encompasses population growth, infrastructure expansion, socio-economic changes accompanied by increased resource consumption, land-use change and pollution, collectively giving rise to profound ecological and societal challenges [6,7]. With the anticipated global rise in urbanization, the conversion of land for urban purposes is expected to intensify, thereby modifying ecosystem structures and functions [3,8]. Urbanization exerts a profound adverse impact on biodiversity by diminishing and fragmenting native habitats and disrupting ecological processes, and thus represents one of the most critical threats to global biodiversity over the past many decades [9–14].

The diversity of life observed today reflects billions of years of evolutionary history molded by natural processes, but it is now under growing influence from anthropogenic activities [15]. Biodiversity plays a vital role in sustaining ecosystem health and is integral to the attainment of the Sustainable Development Goals (SDGs) [16,17]. Yet this critical function is increasingly undermined by urbanization, which drives shifts in species composition, diversity, and community structure, and is a major contributor to the decline and extinction of native species through habitat loss and degradation [18–20]. Globally, there are 36 biodiversity hotspots covering just 2.4% of the Earth's land area but harboring nearly half of all endemic plant species and more than 40% of endemic terrestrial vertebrates [19]. However, these hotspots are increasingly imperiled by escalating anthropogenic pressures, which heighten species extinction risks and contribute to the decline of critical ecosystem services [21–23]. Indeed, for the first time in human history, the pace of species extinction is projected to surpass the rate of species discovery [21]. Therefore, comprehending the dynamics of urbanization is essential for mitigating its environmental impacts and for advancing pathways toward sustainable development. The study estimates that Earth hosts approximately 8.7 million eukaryotic species, revealing that about 86% of terrestrial and 91% of marine species remain undescribed, underscoring the vast gap in our knowledge of global biodiversity [24,25]. Even though many studies have examined how urbanization affects ecological patterns and processes [26–28], knowledge of the spatial and temporal distribution of these impacts on biodiversity remains limited [29]. Our understanding of the relationships between urbanization and biodiversity is particularly insufficient in the global south, where urban growth is projected to be most rapid [29–32]. With urban areas expected to more than double by 2050, assessing their effects on species communities is vital for biodiversity conservation [33,34].

India is recognized as one of the world's 17 megadiverse countries, harboring 7.6% of all mammals, 12.6% of avifauna, 6.2% of reptiles, 4.4% of amphibians, 11.7% of fishes, and 6.0% of flowering plant species [34,35]. Despite this richness, urbanization in India has led to ecosystem degradation, habitat destruction, resource depletion, and biodiversity loss [36,37]. Cities are increasingly facing challenges related to the availability of green spaces, with significant implications for both biodiversity conservation and climate change adaptation [37]. Previous research has documented the adverse impacts of urbanization on a wide range of taxa, including the sharp decline of house sparrow populations across multiple Indian states [38,39], reductions in spider diversity in Guwahati [39], decreased bird species richness in Central India [40], loss of arbuscular mycorrhizal fungal diversity in Delhi [41] and altered ant communities in South India [42].

Mountains account for approximately 24% of the Earth's land surface and encompass nearly half of the world's biodiversity hotspots [43]. In the Indian Himalayan region, several studies have documented the adverse impacts of urbanization on biodiversity. The rapid expansion of hydropower projects, urban sprawl, tourism activities, and the construction of roads and railways—compounded by extreme climate events and global warming has further exacerbated the degradation of natural ecosystems [44–48]. These pressures have led to deforestation, land-use change, simplification of biota, and the promotion of alien species, resulting in habitat homogenization and ecological damage [49,50]. Overpopulation and urbanization have disrupted hydrological systems and increased susceptibility to natural disasters such as landslides and flash floods [50]. Collectively, these studies highlight the imperative for sustainable urban planning and conservation strategies to counteract the detrimental impacts of urbanization on biodiversity in the Indian Himalayan region.

Biodiversity hotspots are regions characterized by exceptionally high levels of species richness and endemism, as well as significant levels of habitat loss and degradation. These areas are of paramount importance for global conservation efforts due to their biological diversity and ecological significance [51]. The Sikkim Himalaya (SH), situated within the Eastern Himalayas (EH) of India, is recognized as one of the 36 global biodiversity hotspots and has also been classified as a crisis ecoregion [52]. Owing to its distinctive topography, varied climatic conditions, and exceptionally rich biodiversity, the SH is considered among the most biologically diverse regions globally [53,54]. Approximately 165 species of flowering plants have been named after Sikkim, of which 58 species are endemic to the region [55,56]. Despite its ecological importance, the Sikkim Himalaya is experiencing rapid urbanization and infrastructure development [56,57]. The influx of people from different states of India has led to the expansion of cities and towns, increased demand for land and natural resources and intensified anthropogenic activities such as mining, agriculture and tourism [58–60]. Urbanization trends in the Sikkim Himalaya are marked by the transformation of natural habitats into built-up areas, fragmentation of ecosystems and consequent biodiversity loss [61,62]. The decline in vegetation cover, expansion of built-up areas and reduction in snow and ice extent highlight the substantial challenges to biodiversity conservation and ecosystem resilience in the Sikkim Himalaya [62].

Despite being a globally significant biodiversity hotspot, the Sikkim Himalaya lacks comprehensive, region-specific studies on the ecological impacts of urbanization. Existing research is fragmented, with limited mapping of urban expansion in biodiversity-sensitive zones, inadequate evaluation of species-level responses particularly for endemic and threatened taxa and insufficient attention to the role of urban green spaces in sustaining biodiversity. Socio-ecological factors, the compounded effects of climate change, and long-term biodiversity monitoring are also rarely integrated. These gaps underscore the need for holistic, interdisciplinary investigations to guide sustainable urban planning and conservation in the region.

Accordingly, this study was undertaken in the Eastern Himalayan state of Sikkim to address four key research questions:

1. How does urbanization alter biodiversity patterns, including species richness, composition and ecosystem functions?
2. What are the principal drivers of urbanization (e.g., infrastructure development, tourism, invasive species, hydropower projects), and how do they contribute to habitat degradation?

In the current study, these research questions form the basis for testing two hypotheses:

H1: *The rapid and unplanned urbanization in the Sikkim Himalaya is strongly associated with biodiversity decline, habitat fragmentation and an increase in invasive alien species.*

H2: *The urban green spaces and eco-sensitive zone policies can mitigate biodiversity loss but remain limited in effectiveness without integrated land-use planning and active community participation.*

The study generates region-specific insights into urban expansion patterns in recent years, identifies biodiversity-sensitive zones at greatest risk and documents species-level responses with a focus on endemic and threatened taxa. It also evaluates the role of urban green spaces in maintaining ecological functions, critically reviews

policy frameworks, and lays the groundwork for adaptive planning and long-term biodiversity monitoring. Together, these contributions provide an evidence-based foundation for guiding biodiversity conservation leading to sustainable development in this global hotspot.

2. Materials and Methods

2.1. Study Area

Sikkim(ca. of 7,096 sq. km; 27°05' to 28°07' N latitudes and 87°59' and 88°56' E longitude), a small and most beautiful state in the eastern Himalayas of India, situated between Nepal to the west, Bhutan and the Tibetan Autonomous Region (TAR) of China to the east, Indian state of West Bengal to the south, and the Tibetan Plateau of the TAR of China to the north is immensely rich in biological diversity due to diverse eco-climatic conditions, extends approximately 114 km from north to south and about 64 km from east to west with wide altitudinal variation from about 300 m to 8598 m [63,64] (**Figure 1**). The state is dominated by the third-highest mountain peak, Kangchenjunga. Major water sources include the Teesta Khangse Glacier and Chho Lhamo in North Sikkim, and Mount Kabru in the southern Kangchenjunga region, which feed the Teesta and Rangit rivers, respectively [65,66]. Sikkim Himalaya is home to diverse ethnic communities, including its indigenous Lepchas, Bhutias and Nepalese populations.

Figure 1. Location of study area in India with urban town of Gangtok.

2.2. Methodology

This study employed a narrative literature review methodology that provides a qualitative synthesis of current knowledge on impact of Urbanization on Biodiversity in Sikkim. The approach combines systematic literature identification with thematic analysis to develop a holistic understanding of urbanization impact on biodiversity. We collected literature published from 1990 to 2024. For practicality, we included only English language literature for the current study.

Literature Search Strategy: The comprehensive literature search was conducted across multiple electronic databases including Web of Science Core Collection, Scopus, PubMed/MEDLINE, Google Scholar, JSTOR, ScienceDirect, Springer Link, and Wiley Online Library. The search strategy employed both primary keywords ("urbanization AND bird*," "Biodiversity AND Sikkim*") and secondary keywords ("Urbanization Impact* AND Fauna*," "Land use change AND Biodiversity") using appropriate filters.

Study Selection methodology: The study selection followed a systematic three-stage process according to PRISMA guidelines (**Figure 2**)

Identification Phase: Initial database searches identified 1450 records, with an additional 250 records from other sources, totaling 1730 records.

Screening Phase: After removing 210 duplicates, 1520 records underwent title and abstract screening, resulting in 1000 exclusions due to the geographic irrelevance and thematic mismatch and 500 articles proceeded to full-text assessment.

Eligibility Phase: Full-text assessment of 500 articles led to the exclusion of 300 articles for various reasons: wrong focus (109), not urban context (85), not focus on Sikkim (74), methodology issues (31), and language barriers (40).

Final Inclusion: Total of 161 studies were ultimately included in the qualitative synthesis, forming the evidence base for this comprehensive review.

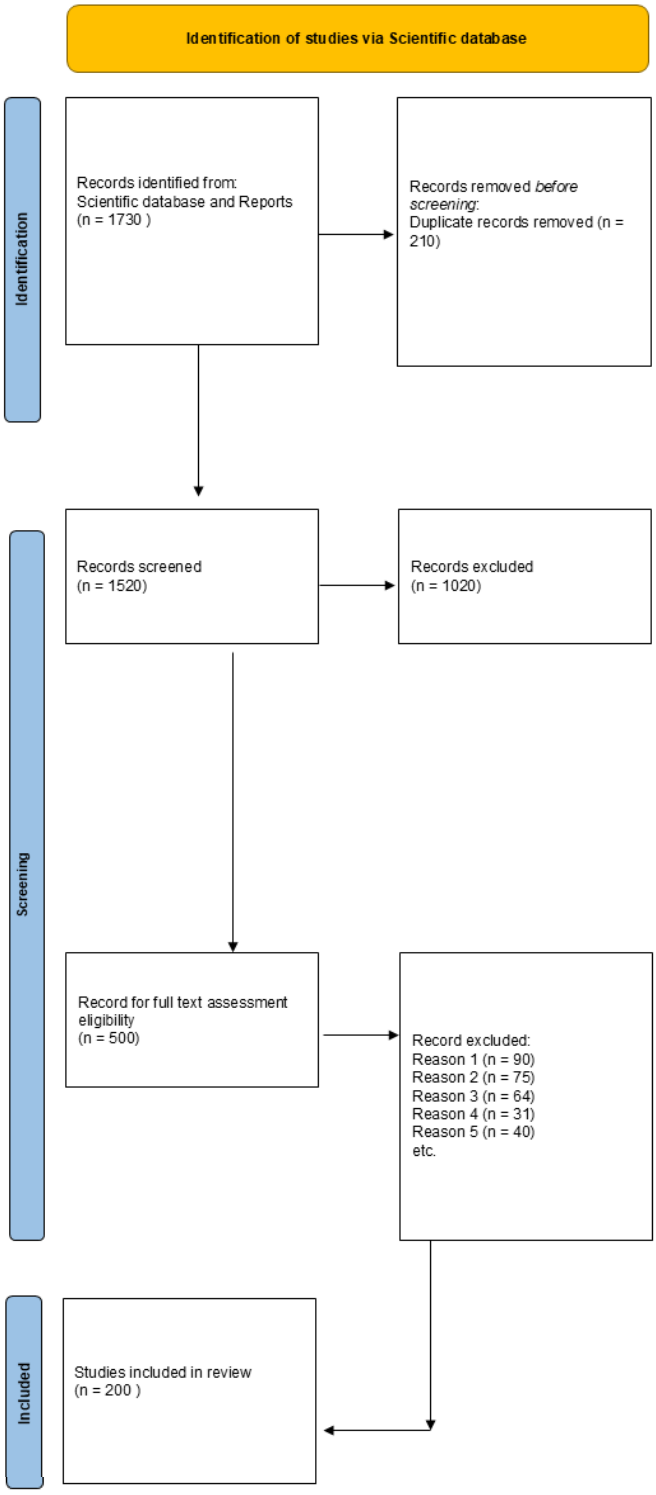


Figure 2. PRISMA Flow Diagram for Literature Review.

3. Results and Discussion

3.1. Historical Background

The historical trajectory of urban development in the Eastern Himalayan state of Sikkim has been shaped by a complex interplay of socio-political and economic factors. Before its merger with India in 1975, when Sikkim functioned as a kingdom under the Chogyal monarchy, processes of urbanization remained limited and relatively underdeveloped [66]. Following Sikkim's accession to India, urbanization gained momentum with the establishment of government institutions, educational facilities, and infrastructure projects. The construction of roads, bridges, and utilities accelerated urban growth, attracting migrants from neighboring states transforming it predominantly from a rural state to one undergoing rapid urban development. Until 1970, urbanization was minimal, but the post-merger period witnessed accelerated urban growth [67]. The state's urban population increased dramatically from 2% in 1951 to 11% in 2011, while the number of towns grew from 1 in 1981 to 8 in 2001 [67]. This transformation gained further momentum through targeted policy interventions, most notably the North East Industrial and Investment Promotion Policy of 2007, which stimulated industrialization and facilitated the influx of migrant labor [68]. Rural-urban migration became a primary driver of urban population growth, with people attracted by better employment opportunities, urban facilities, and improved lifestyles [67]. The period from 2000 to 2024 also saw the emergence of commercial hubs, residential neighborhoods and recreational areas in different districts of Sikkim. Urbanization in Sikkim has been associated with economic growth, leading to significant reductions in poverty and unemployment, despite concerns regarding employment opportunities for outsiders [68,69].

3.2. Biodiversity of Sikkim Himalaya

Recognized as one of the 36 global biodiversity hotspots, Sikkim, part of the Eastern Himalaya Biodiversity Hotspot, harbors a remarkable number of endemic and endangered species [70,71]. The Eastern Himalayas are among the richest regions of biodiversity on Earth, particularly notable for avian diversity, with numerous endemic species and subspecies [72]. Sikkim covering just 0.2 % of the geographical area of the country has 26% of the country's total biodiversity and being a part of the Eastern Himalayas has been identified as one of the 36 global biodiversity Hot-Spot (**Table 1**), largely driven by its wide altitudinal range of 300–8598 m which supports diverse ecoregions [70–73]. Nevertheless, several groups, including bacteria, viruses, algae, fungi, lichens, bryophytes, protista, molluska, arthropods, other invertebrates and protochordates, remain largely unexplored in the region [73]. The tremendous diversity of insects like beetles and moths as well as a host of other life forms is yet to be enumerated [72].

Table 1. A biodiversity profile of Sikkim Himalaya.

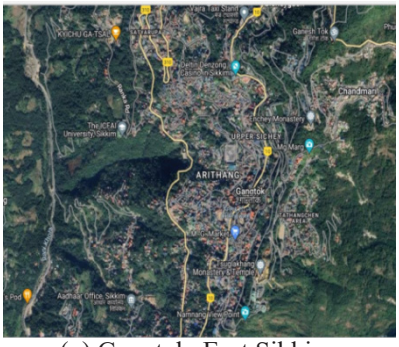
Flora	No. of Species	Fauna	No. of Species
Flowering Plants	5500	Mammals	144+
Orchids	557	Bees	30
Rhododendrons	38	Beetles	994
Conifers	16	Birds	568
Bamboos	28	Butterflies	689
Ferns and Ferns allies	362	Moths	7000
Tree Ferns	9	Insects	5892
Primulas	30	Fishes	48
Oaks	11	Frogs	16
Medicinal plants	1681	Lizards and Snakes	92
Magnolia	12	Reptiles	33
Lichens	506	Amphibians	50
Tree and tall Bamboos	717		
Small Grasses	257		

Source: National Biodiversity Strategy and Action Plan (NBSAP)—Sikkim State (2002); Sikkim Biodiversity Action Plan, DFEWM, GOS.(2011); ENVIS, 2025.

3.3. Urbanization Trend in Different Towns of Sikkim Himalaya

In Sikkim, the majority of the population is concentrated in the urban areas of the East district (80%), followed by the South district (13%), with comparatively smaller proportions residing in the West (4%) and North (3%) districts [67]. Urbanisation in Sikkim is not limited to Gangtok; several other towns are also experiencing similar transformations. For instance, Namchi, the capital of South Sikkim, is witnessing a rapid construction boom that is reshaping it from a modest district headquarters into a prominent urban centre [56]. Similarly, Chungthang in North Sikkim is undergoing urbanisation, largely driven by state-led development initiatives [74]. Similarly, other towns in Sikkim such as Jorethang, Rangpo, Singtam, Rhenock, Rongli, Mangan, and Pakyong have also made significant advances in the process of urbanisation. Urban development in Gangtok has altered land use, modified slopes, and fragmented natural habitats, reshaping the landscape and creating man-made environments [75]. With regard to Gangtok, the population growth rate during the decade 1991–2001 was recorded at only 17.30 %. However, between 2001 and 2011, the population of Gangtok increased dramatically from 29,359 to 98658, reflecting an approximate growth of 235.97 % [67].

Gangtok, as the state capital, in the East district has expanded rapidly through tourism growth, rural in-migration, and infrastructure investments, leading to dense hillside construction, traffic congestion and increased landslide risk (**Figure 3a** and **Figure 4a,b**). Pakyong, spurred by the new airport and better road links, is converting agricultural land into residential and commercial areas but faces service slope-stability concerns (**Figure 3b**). Singtam, a key trade junction, is growing as a market hub with strip development along transport corridors, bringing drainage stress, floodplain encroachment, and traffic pressures (**Figure 3c**). Rangpo, the gateway to West Bengal, is experiencing industrial and logistics-driven growth with warehouses and roadside settlements, creating congestion and environmental pressures from largely unplanned expansion (**Figure 3d**). Urbanization in North district town—Mangan and Chungthang is driven by administrative importance, tourism, and hydropower development. Mangan has grown gradually as North Sikkim's district hub, with residential, commercial, and government infrastructure expanding along highways and slopes, straining water, waste, and drainage systems (**Figure 3e**). Chungthang's growth is linked to hydropower projects, worker settlements, and strategic connectivity, leading to rapid, uneven expansion along river valleys (**Figure 3f** and **Figure 4c,d**). Both towns face high landslide and flood risks, limited municipal services, and environmental pressures due to development on steep, fragile terrain. Urbanization in South district, Jorethang and Namchi is driven by trade, administration, and tourism. Jorethang has expanded along the NH10 highway with commercial and residential development, putting pressure on traffic, drainage, and flood-prone areas (**Figure 3g**). Namchi's hillside growth accommodates administrative, residential, and tourism infrastructure, stressing slopes, water supply, and waste management (**Figure 3h** and **Figure 4e,f**). Both towns face environmental risks from slope modification, unplanned development, and infrastructure strain. In west Sikkim, Geyzing is moderately urbanized as West Sikkim's administrative center and a gateway to Pelling, with residential and commercial growth concentrated along valley floors and road corridors serving trade, administration and tourism (**Figure 3i**).



(**a**) Gangtok, East Sikkim.

(**b**) Pakyong, East Sikkim.

(**c**) Singtam, East Sikkim.

Figure 3. *Cont.*


(**d**) Rangpo, East Sikkim.


(**e**) Mangan, North Sikkim.


(**f**) Chungthang, North Sikkim.

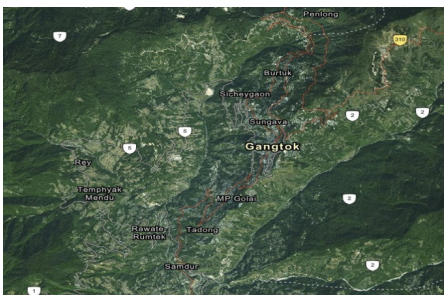

(**g**) Jorethang, South Sikkim.


(**h**) Namchi, South Sikkim.


(**i**) Geyzing, West Sikkim.

Figure 3. Urbanization at various states in different towns of different districts of Sikkim (2025).

(**a**) Gangtok, East Sikkim (13.10.21).

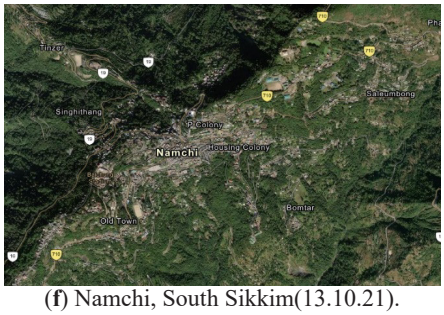


(**b**) Gangtok, East Sikkim (12.11.2014).

(**c**) Chungthang, North Sikkim (12.11.2014).

(**d**) Chungthang, North Sikkim (13.10.2011).

(**e**) Namchi, South Sikkim (12.11.2014).



(**f**) Namchi, South Sikkim(13.10.21).

Figure 4. Urbanization during different decades in different towns of Sikkim.

3.4. Biodiversity Loss in Sikkim Himalaya

Local subsidence needs caused degeneration in the temperate forest habitat by causing decline in tree species number and change in tree species composition in Mamlay watershed in South Sikkim [76]. In Sikkim Himalaya, a substantial number of species have been recorded from its forests and wetlands [77]; although comprehensive biodiversity assessments have yet to be conducted. Despite this ecological richness, the Sikkim Himalaya faces multiple threats to biodiversity, including population growth, urbanization, infrastructure development, unregulated mass tourism, climate change and the loss of traditional knowledge [78–82]. Perceived threats to biodiversity of Sikkim are deforestation, air pollution, poaching of animals and smuggling of plants, introduction of exotic species, unplanned tourism, inappropriate waste management, climate change, invasive alien species, forest fire, change in land use pattern, loss of traditional knowledge and popularization of hybrids [83,84]. Furthermore, despite existing ban on wildlife trade and the collection of non-timber forest products (NTFPs), illegal harvesting of NTFPs and poaching of wild animals continue to pose significant threats to the biodiversity of Sikkim [81]. Biodiversity loss in Sikkim has been primarily attributed to overpopulation, deforestation and various anthropogenic pressures [83–89].

3.5. Impact of Urbanization on Biodiversity

3.5.1. Impact of Infrastructure Development

Previous studies in Sikkim Himalaya reveal that the rapid developmental programme, encroachment by people for food and fuel and frequent landslide were the main causes of the depletion of the rich floral diversity [89]. Previous botanical studies in Gangtok found that the biological spectrum of Gangtok reveals the similarity with the world spectrum in life forms of Cryptophytes and Hemicrytophytes [90]. Furthermore, another study recorded 37 medicinal plant species used in 52 traditional treatment for different ailments by the urban population of Gangtok [91]. Nonetheless, in the absence of any scientific studies in the past almost two decades (2004–2022), it is not possible to ascertain whether the frequency, density and abundance of these 37 medicinal plant species used in 52 traditional treatment have increased or decreased. Previous studies have shown the increase of species/family richness and density of vegetation(Trees, herbs and shrubs) from the lower end to the upper end of the Gangtok-Deorali ridge, thereby following a natural progression from low to high along Gangtok-Deorali ridge [92]. However, in the past decade (2010–2020) there have been rapid developmental activities along this ridge in terms of residential buildings, and tourism resorts. Consequently, the original remnant natural forest patches/habitats have been removed to a considerable extent. The rapid development in urban infrastructure, economic opportunity, modern amenities, education, living standards etc attracted the rural people to pull towards urban areas [57,68,69]. Over the past two decades(2005–2025), most Sikkim towns have experienced rapid private construction with little regard for aesthetics, building regulations, civic amenities, or traditional materials and styles [79]. In another study conducted on land use/land cover (LULC) dynamics in the last decade (2014) revealed, considerable reduction of forest cover and the increase in built-up in the Gangtok area during the past 20 years [93]. Poorly planned construction of buildings and increase road network in Sikkim has caused disturbance to the fragile ecosystem of Sikkim resulting in biodiversity loss [54]. Population growth and urbanization in Sikkim have negatively impacted the physical environment [94].

3.5.2. Impact of Tourism

Tourism activities in Sikkim have exerted significant adverse impacts on local ecosystems, particularly through the intensified extraction of fodder, firewood and timber resources. Along the Yuksam–Dzongri trekking corridor in West Sikkim, the collection of substantial amounts of firewood for cooking and heating has been identified as a major driver of forest fragmentation and habitat destruction [95]. These extraction pressures contributed to shifts in species composition and have hindered the natural regeneration of key firewood species, thereby exacerbating ecological degradation along this heavily frequented tourist route [86,95,96]. There have been reports of the increase in the demand of basic resources such as green fodder, fuelwood and Non Timber Forests Products(NTFP's) by in community around the protected areas such as Maenam Wildlife Sanctuary in Sikkim which is also a tourist spot thereby

causing immense damage to vegetation due to uncontrolled tourism [97,98]. The rich biodiversity of the Sikkim Himalaya has been degraded by rapid urbanization, deforestation, and construction activities, especially in tourism-intensive areas where floristic diversity has notably declined [99]. Any unsustainable developmental activities inside and in the close peripherals of the protected area would be detrimental to the survival of avian diversity as reported during the last decade in another protected area of Fambhonglho Wildlife Sanctuary [100]. These practices directly affect avi-tourism potential of a tourist spot. The traditional practice of sky burials among Tibetan nomads once supported the conservation of high-altitude vultures like the Bearded Vulture (*Gypaetus barbatus*) and Himalayan Griffon (*Gyps himalayensis*), but this practice has declined over the past few decades [101]. The extension of infrastructural development, vehicular accessibility, and state-sponsored aid into remote interior regions has been concomitant with a rise in anthropogenic pressures. These include escalating incidences of wildlife poaching and snaring, clandestine large-scale harvesting of *Ophiocordyceps sinensis* (caterpillar fungus) from protected areas, degradation of sacred landscapes through unregulated tourism and a range of other deleterious environmental and socio-cultural impacts [102–104]. Simultaneously, the absence of systematic written documentation and continued reliance on oral traditions, when compounded by rapid development and modernization, has accelerated the erosion of indigenous ecological knowledge systems, leading to the irretrievable loss of traditional wisdom in biodiversity conservation [102–105]. In the past decade, an incident of bio-piracy was reported in West Sikkim, where an American tourist allegedly took seeds of the rare *"Dalle khorsani,"* cultivated them abroad, and later publicized the crop on social media as *"American Dalle"* [104,105]. Prolonged urbanization and intensified tourism activities have been major drivers of fragmentation and degradation of the native woodland ecosystems in this mountainous region [106]. Prolonged urbanization and tourism have caused fragmentation and degradation of the original woodlands in Gangtok's municipal area of the Sikkim Himalaya [106]. In the last two decades, the natural water sources have decreased in Gangtok [107].

3.5.3. Impact of Invasive Alien Species

Invasive and exotic species are responsible for depletion of native species and ultimately changing the ecological pattern of that area [108]. Previous studies on exotic plants of Sikkim have identified 16 species such as *Achyranthes aspera, Ageratum conyzoides, Bidens biternata, Calceolaria Mexicana, Cestrum aurantiacum* and *C. elegans, Crassocehalum crepidioides, Croton bonplandianum, Erigeron karvinskianus, Eupatorium adenophorum, Ipomoea nil, Lantana camara, Mikania micrantha, Oxalis latifolia, Primula malacoides, Solanum viarum, Xanthium strumarium etc.* [99]. *Ageratum conyzoides, Lantana camara, Parthenium hysterophorus* etc. are some of the invasive alien species(IAS) in and around Gangtok. Total number of IAS in Gangtok has been reported to be 22 [107]. Urbanization can increase the invasive potential of alien species [108–110]. Urban environments function as critical gateways for the introduction and dissemination of invasive species, facilitated by trade, transportation networks and diverse human activities [111,112]. The introduction of invasive species represents a major consequence of urbanization in the Sikkim Himalaya, posing a substantial threat to biodiversity by altering ecosystem structures and diminishing habitat quality for native flora and fauna [113]. The invasive alien species such as Titepati (*Artemisia milagirica*) and Banmara (*Eupatorium adenophorum*) have proliferated extensively across various regions of Sikkim [81]. Although the Sikkim Himalayan zones support a rich diversity of endemic species, the expansion of invasive species threatens their survival [113,114]. The common invasive floral species are *Mikania micrantha, Lantana camara, Ageratina adenophora, Ageratum conyzoides, Chromolaena odorata, Bidens pilosa* and *Parthenium hysterophorus* which are threat to native biodiversity by displacing native vegetation and altering habitat structure [114]. A total of 114 invasive alien species have been documented in the Sikkim Himalayas, many of which have spread across different altitudinal ranges and areas of anthropogenic disturbance, exerting adverse impacts on biodiversity [112–116].

3.5.4. Impact of Hydropower Development, Water Pollution

During the last two decades (2000–2020), several pharmaceutical industries have been set in the East and South districts of Sikkim particularly along major highways like NH-10, NH-710, NH-510, NH-710A and near

the tropical eco-belts surrounding Teesta, Rangit, Rangpo, and Rani Khola [115]. Dam construction affects both terrestrial and aquatic biodiversity, with the most pronounced impacts on riverine ecosystems and their functions [116-118]. River ecosystems in Sikkim are under tremendous pressure due to various developmental activities including sand mining, deep riverbed excavation and extraction, river quarrying and unprecedented alteration of the natural flow of the river [119–122]. Earlier studies have reported that due to downstream projects, particularly the Teesta Low Dam III, blocked the upstream migration of two fish species *Tor putitora* and *Anguilla bengalensis*, preventing them from reaching their breeding grounds in the Rangit and upper Teesta rivers. In the Sikkim Himalaya, 06 hydroelectric projects have been proposed along the Teesta River, of which two (i) Teesta Stage-III and (ii) Stage-V have already been constructed and are presently operational [121]. Previous studies have reported extremely high microbial pollution from pharmaceutical plants in Sikkim [122]. However, the impact of such pollution on aquatic flora and fauna has not been studied so far.

3.5.5. Land-Use Change and Forest Degradation

Deforestation, landslides, high-altitude human settlement, development of power projects, uncontrolled grazing, and the disruption of critical ecological linkages collectively appear to contribute to the risk of species extinction in Sikkim [123]. The effect of deforestation on vascular epiphytes in Sikkim Himalaya has been reported before in the Nagi-Namthang area and in East Sikkim forest habitat [124,125]. Epiphytes in forest canopies support animal abundance and diversity by providing resources and contributing to ecosystem processes [126]. According to Forest Survey of India, the area under dense forests seems to have marginally declined during the period 2001 to 2003 [127]. This reduction in forest cover and growth in built up areas is closely associated with the loss of habitat for several sensitive species, thereby posing significant risks to their survival [128,129]. Sikkim Himalaya faces numerous threats to biodiversity due to land use change induced by the increase in population, infrastructure development, urbanization, and climate change, unplanned and mass tourism, loss of rich traditional knowledge [79,81,89,130]. A land-cover change over a 23-year period for the Sikkim Himalaya for the elevation range 800–2800 m revealed that the tropical montane forests continue to decline in the Sikkim Himalaya, particularly at lower elevations [129]. Land-use modifications are often associated with shifts in understorey species composition, which may subsequently affect the functioning and stability of ecosystems [131,132]. Currently, the trends and patterns of urbanization in Sikkim Himalaya are characterized by rapid population growth, spatial expansion and vertical development [133].

3.6. Biodiversity Loss due to Urbanization in Gangtok

The population of the most urbanized habitat of study area, Gangtok has surged in recent decades [133], fuelled by in-migration and tourism [134,135]. This influx of people has led to the increase of built-up areas, the proliferation of informal settlements, and the intensification of land-use activities. The impacts of population growth and migration on urban expansion in Gangtok are inherently complex and multidimensional. These processes are often associated with stimulating economic dynamism, fostering cultural diversity, and enhancing social vibrancy, which may collectively contribute to the city's livability and attractiveness. At the same time, they tend to exert increasing pressures on natural resources, place considerable strain on infrastructure systems, and contribute to the intensification of environmental degradation. Over the past decade, forest fire has increasingly been recognized as a potential environmental threat and 1050 forest fires have been reported in the last 22 years (2000–2022) [83,136–138]. In Sikkim, empirical studies indicate that such events are predominantly ground fires, which can substantially affect forest biodiversity [137]. Furthermore, forest cover in the state has exhibited little improvement since 2011, while recurrent natural hazards have exerted a markedly negative influence on its forest ecosystems [138,139].

Several forest-urban gradients are under the transition phase due to the change in frequency, density, abundance, structure and composition of vegetation due to land use change accelerated by various developmental activities including tourism. Previous vegetation studies conducted along a Deorali-Gangtok ridge in East Sikkim showed high frequency, rich density and abundance of *Alnus nepalensis,*

Saurauia napaulensis, Prunus cerasoides, Schima wallichi, Macaranga pustulata etc [92]. However, with the establishment of tourist resorts and urbanization, there has been change in the structure and composition of forest cover during the last 15 years along this gradient. This pattern is applicable to those entire hill ecosystems where urbanization is occurring at rapid pace. Ecologically, the reduction of tree cover poses risks to the stability and functioning of ecosystems, with potential consequences including altered hydrological cycles, increased soil erosion and diminished carbon storage capacity [139].

The Ministry of Urban Development (Government of India) launched Smart Cities Project on 25 June 2015 envisioning cities as engines of growth for the economy of every nation, including India. Gangtok was also selected to be developed as one of the 100 smart cities in India. As per the guidelines of the smart cities, 'sustainable environment' is one of the core infrastructure elements in a Smart City. In this regard, development of green field in a previously vacant area using innovative planning has been planned as a strategy for smart city development. Notwithstanding, the developmental activities related to smart cities (such as construction of new footpaths, multi-level car park plazas, feeder roads, road and junction) improvement to ease traffic congestion in town has resulted in removal of ornamental trees such as Cherry tree *(Prunus sp.),* Coral tree *(Erythrina sp.)* and nectar providing trees such as Ghurpees *(Leucosceptrum canum)* etc. from different locations of Gangtok consequently affecting the ecological characteristics of the area. Smart cities may have an adverse effect on the environment in terms of drainage, solid waste and greenhouse gases [139]. The smart city project in Gangtok has resulted in tree felling for road widening, green belt zone encroachments, habitat fragmentation, reduction of natural water sources. Declining habitat availability is frequently associated with heightened biodiversity loss, which may contribute to species extinctions [140–142].

3.7. Threat and Challenges Issues, Policy and Management Strategies

Threats to biodiversity in hotspots are largely the same as those observed worldwide, although they tend to be more severe in these regions [142]. Among these, habitat fragmentation, degradation, destruction, and loss represent pervasive pressures affecting hotspots [142,146]. Moreover, the anthropogenic acceleration of climate change further amplifies the impacts of habitat fragmentation, degradation and loss [143,147].

In the Indian Himalayan Region, it was highlighted decades ago that traditional biodiversity systems were rapidly declining, thereby necessitating innovative policy and programmatic interventions with an emphasis on enhanced community participation [144]. To fulfill India's obligations under the Convention on Biological Diversity (CBD) and to effectively implement the Biodiversity Act, 2002 at the state level, the Government of Sikkim (GoS) established the State Biodiversity Board (SBB). However, the Board became operational only in 2014, following the initiation of the MoEFCC-UNEP-GEF Access and Benefit Sharing (ABS) Project by the National Biodiversity Authority (NBA) in 2012 [145]. The State Biodiversity Board (SBB) is mandated to document People's Biodiversity Registers (PBRs) at each Gram Panchayat Unit (GPU) in Sikkim, with active involvement of local communities and traditional knowledge holders. However, the constitution of the Biodiversity Management Committee (BMC) has raised question on their jurisdiction and JFMC's and EDC's are responsible for managing the reserve forest and protected areas respectively [145]. Furthermore, the maintenance of PBRs plays a vital role in biodiversity conservation in Sikkim by documenting and preserving traditional ecological knowledge, monitoring biodiversity changes, and promoting community-led conservation. Nevertheless, identifying motivated individuals willing to undertake the PBR exercise has been challenging, which in turn has affected the overall quality of the registers [145]. According to recent research, a total of 196 PBRs have been documented and completed in Sikkim, encompassing information on biological resources (BRs) and associated traditional knowledge (TK), which demonstrate potential for Access and Benefit Sharing (ABS) [146]. Nonetheless, urbanization in Sikkim creates cultural, ecological, administrative, and knowledge-based challenges that make it harder to prepare, update, and maintain meaningful PBRs. There are many challenges in preparing and maintaining more People's Biodiversity Registers (PBRs) in Sikkim specifically due to urbanization. Urbanization often leads to cultural shifts, with younger generations moving away from tradition-

al livelihoods like farming, herbal medicine, or foraging. As a result, local biodiversity knowledge is disappearing, making it difficult to document accurate and detailed information for PBRs. Furthermore, with the rapid urban expansion converts forests, agricultural fields, and wetlands into built-up areas, natural habitats are lost or fragmented, the biodiversity to be documented itself declines, making PBR preparation less meaningful or more challenging. In more urbanized or peri-urban areas, people may prioritize economic development over biodiversity conservation. Communities may view PBR exercises as less relevant to their immediate needs like housing, infrastructure or job opportunities.

Biopiracy, coupled with ongoing developmental activities, poses a substantial threat to biodiversity and the associated traditional knowledge of indigenous and local communities [145,146,105,106]. Sikkim shares transboundary borders with China, Nepal, and Bhutan, making it challenging to regulate the illegal trade of biological resources [145]. Consequently, the issue of biopiracy remains prevalent in the region, though much of it goes undocumented. Moreover, the invasive alien species poses threat to the native biodiversity of a region by its adverse impact on local flora and fauna in terms of decreasing species diversity and richness, changes in composition and community structure. With the rapid pace of urbanization in different parts of the state in the coming years, the spread of IAS will surely wipe out the native, rare, endemic biodiversity in the natural habitats thereby disrupting the ecology of the area.

The open forest in the Khangchendzonga Biosphere Reserve, Sikkim has decreased by 2.81% (approx.) from 2000 to 2009 [148]. The lack of mainstreaming of biodiversity conservation into the various developmental plans, which sometimes results in unplanned and detrimental anthropogenic activities, poses an additional indirect threat [149]. Existing policies and regulations related to urban development and biodiversity conservation in Sikkim Himalaya provide a framework for addressing the complex challenges of urbanization and biodiversity loss. The region has enacted various laws and policies aimed at promoting sustainable development, protecting natural habitats, and conserving biodiversity. One such policy is the Sikkim Biodiversity Action Plan (2002), which outlines strategies and actions for the conservation and sustainable use of biodiversity in the state. The plan emphasizes the need for integrated approaches that combine biodiversity conservation with socio-economic development, cultural preservation, and traditional knowledge systems. Additionally, Sikkim Forest, Water Courses and Road Reserve (Preservation and Protection) Act, 2020 consolidates laws related to forests, forest produce, watercourses, and road reserves.

In order to conserve and protect the area around the protected areas of the State, and to propagate the improvement and development of the wildlife therein and to prohibit industries, operations or processes around the boundary of 8 PAs of the State, the Central Government in consultation with Ministry of Environment, Forests and Climate Change (MoEFCC) has declared certain areas around the 8 PAs of the State as Eco-Sensitive Zones in the year 2014. The declaration of Eco-Sensitive Zones (ESZs) in Sikkim not only plays a crucial role in mitigating the adverse effects of urbanization on biodiversity by acting as a buffer between protected areas and urban or developmental activities but also protecting biodiversity from the direct and indirect impacts of urbanization by maintaining ecological integrity while promoting sustainable development around critical habitats.

The expansion of built-up areas has profound implications for urban development and biodiversity, primarily through habitat fragmentation that disrupts ecological connectivity and species migration [150–154]. Such fragmentation isolates populations, reduces genetic diversity, and heightens ecosystem vulnerability [149]. Correlations with tree cover dynamics further reveal trade-offs between urban growth and green space, emphasizing the need for integrated land-use planning that balances development with conservation [153–158]. Challenges in implementing effective management strategies for urbanization and biodiversity conservation in Sikkim Himalaya include limited institutional capacity, inadequate funding, conflicting land-use priorities, and lack of awareness and community participation. Urban planning and development frequently prioritize short-term economic benefits at the expense of long-term environmental sustainability, resulting in unsustainable land-use practices, habitat degradation, and biodiversity loss. Furthermore, weak enforcement of environmental regulations and corruption undermine conservation efforts and exacerbate environmental degradation. To address

these challenges, policymakers and stakeholders in Sikkim Himalaya should prioritize the following recommendations (**Figure 2**):

1. Strengthening the governance mechanisms and institutional capacity to mitigate the impact of urbanization on biodiversity by preserving green spaces, urban parks and incorporating natural habitats into urban design. The green spaces provide habitats for insects, birds, butterflies etc.
2. Integrating biodiversity considerations into urban development policies and practices, including green infrastructure by providing incentives for green building practices. Government can enact policies and legislations to promote biodiversity conservation in urban habitats.
3. Enhancing public awareness and fostering community participation in decision-making processes concerning land-use planning and natural resource management.
4. Promoting sustainable land-use practices such as agroforestry, organic farming, and community-based natural resource management to strengthen ecosystem resilience and support local livelihoods.
5. Implementing ecosystem based strategies for climate change adaptation and mitigation, including reforestation, watershed management, and ecological restoration.
6. Supporting research and monitoring initiatives to evaluate biodiversity and ecosystem status, identify major threats and vulnerabilities, and guide evidence-based decision-making.

A conceptual framework of the current study that illustrates the intricate linkages between urbanization drivers, emerging threats, biodiversity impacts and potential mitigation strategies in the Sikkim Himalaya is presented in **Figure 5**. Climate change is increasingly altering agriculture, forestry, water resources, and biodiversity in the Sikkim Himalaya, while rapid urban expansion continues to replace traditional green spaces with built habitats [155–156]. In this transforming landscape, urban sacred forests and remnant patches of native vegetation provide critical ecosystem services that strengthen climate resilience by regulating microclimates, enhancing carbon sequestration, and buffering against extreme weather events. These green spaces also function as biodiversity refugia, supporting native species, maintaining ecological corridors [157,158]. Recognizing and integrating such nature-based assets into urban planning, zoning, and climate adaptation strategies is therefore essential for reconciling development pressures with long-term ecological sustainability in the Sikkim Himalaya. **Table 2** summarizes the major threats posed by urbanization to the biodiversity of the Sikkim Himalaya and outlines key mitigation strategies.

It has been demonstrated before that small, isolated patches of vegetation such as small gardens, tree stands, roadside greenery, and vacant lots play a critical ecological role in biodiversity conservation in urban habitats [158,159]. These patches not only offer nesting, foraging, and shelter sites for birds, pollinators (bees, butterflies), small mammals, reptiles, and soil organisms but also support native plant species that can persist or recolonize within urban habitats. Nevertheless, these patches of tree stands, roadside greenery, and vacant lots are rapidly being replaced with concrete structure after deforestation in the urban habitats of Sikkim Himalaya as observed in Gangtok urban habitat (**Figure 6a–c**). Even the native tree species such as *Alnus* spp., *Michelia* spp., *Castanopsis* spp. are removed for household construction, firewood collection in the suburban and rural habitats of the study area such as sang, duga for timber (**Figure 6d–f)**. The Sikkim government imposed a ban on livestock grazing in reserved forest areas, plantations, and water source areas in 1998 to address ecological degradation. However, the fodder collection near water bodies are still in practice as observed in the Mazitar suburban area of Rangpo urban habitat (**Figure 6g**). The pharmaceutical industries along the Teesta river stretch between the industrial corridor stretch between Singtam and Rangpo (**Figure 6h**) as well as hydro power projects at lower elevation zone such as Sirwani, East Sikkim (**Figure 6i**) is a threat to native biodiversity particularly birds, butterflies and fishes since operation of these power projects is detrimental to nesting, foraging, and shelter sites for birds, pollinators (bees, butterflies) as well as the spawning site for aquatic fauna such as fishes. Besides, the invasive alien species—*Eupatorium sp* (**Figure 6j**), *Mikania sp* (**Figure 6k**), *Ageratum conyzoides* (**Figure 6l**)*, Bidens Pilosa* (**Figure 6m**)*, Ipomoea sp* (**Figure 6n**),

and *Parthenium sp* (**Figure 6o**) at different elevation zones including tropical, subtropical and along forest-urban gradient of the Sikkim Himalaya is a threat to biodiversity as observed along the river bed sites of Singtam, Rangpo and urban habitat of Namchi. These species spread due to urbanization as reported in previous studies [160].

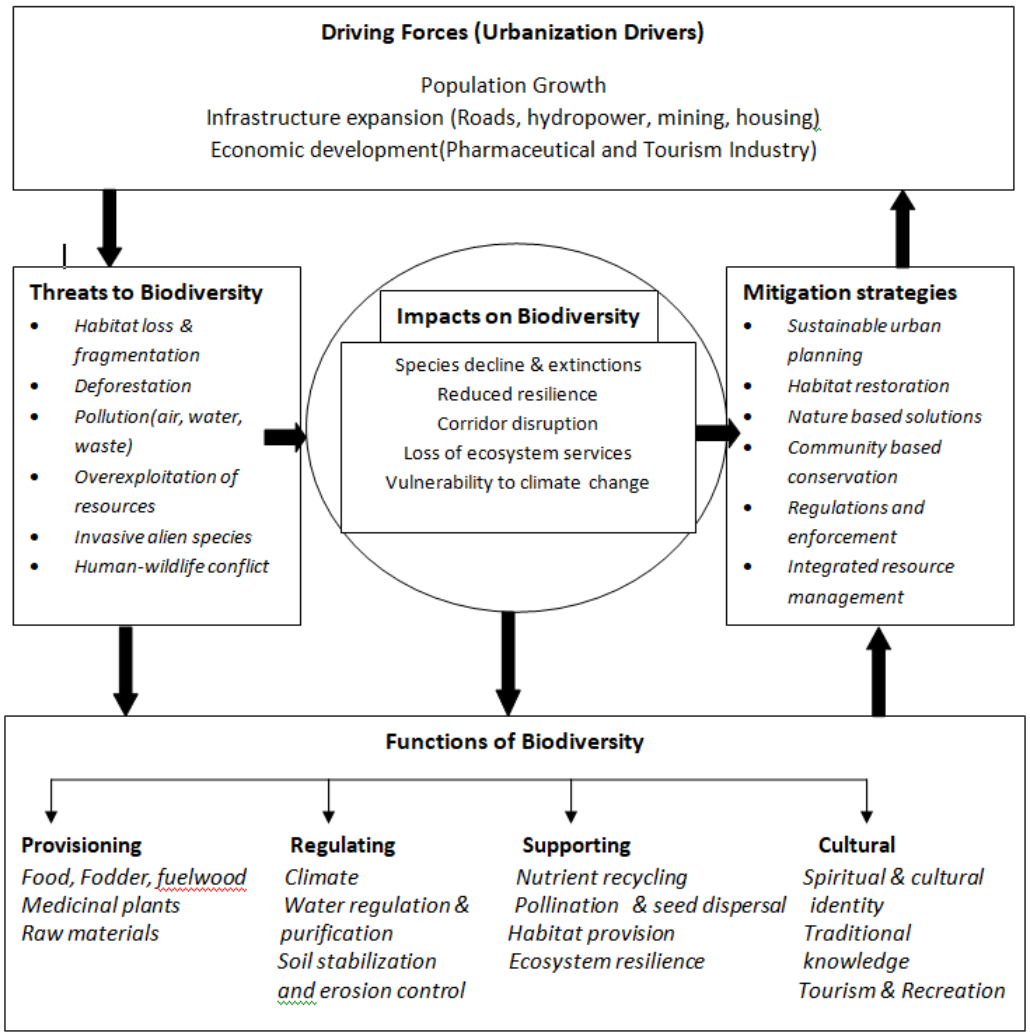


Figure 5. Conceptual framework/diagram showing the relationship between urbanization drivers, threats, biodiversity impacts and mitigation in Sikkim Himalaya.

Table 2. Major threats posed by urbanization to the biodiversity of the Sikkim Himalaya and key mitigation strategies.

Threats Types due to Urbanization	Specific Impacts on Biodiversity	Mitigation Strategies
Habitat loss & fragmentation	• Conversion of forests to built-up areas • loss of endemic species habitats • disruption of ecological corridors	• Sustainable urban planning Establishment of Eco-Sensitive Zones (ESZs) integrated land-use planning to maintain habitat connectivity
Deforestation & land-use change	• Decline in forest cover, soil erosion • reduced carbon storage • altered hydrological cycles	• Large-scale reforestation and afforestation • Promotion of organic farming • State Green Mission
Infrastructure development (roads, hydropower, construction)	• Landscape modification, • slope destabilization • disturbance to wildlife	• Environmental Impact Assessments (EIAs); • eco-friendly construction guidelines; • strict enforcement of building regulations

Table 2. *Cont.*

Threats Types due to Urbanization	Specific Impacts on Biodiversity	Mitigation Strategies
Tourism pressure	• Forest degradation, littering, • extraction of firewood • disturbance to wildlife	• Regulation of tourism activities; • promotion of eco-tourism; • carrying capacity assessment
Invasive alien species	• Displacement of native flora and fauna • alteration of ecosystem structure	• Regular monitoring and removal programs; • public awareness campaigns; biosecurity measures
Pollution (air, water, waste)	• Degradation of soil and water quality • Threats to aquatic biodiversity	• Waste management systems; • pollution control laws; • adoption of green infrastructure
Climate change interactions	• Increased vulnerability of high-altitude ecosystems • species range shifts	• Climate adaptation strategies • ecosystem-based approaches (watershed management, restoration)
Loss of traditional ecological knowledge	Erosion of indigenous conservation practices	• Documentation of People's Biodiversity Registers (PBRs); • community-based conservation initiatives

Source: Compiled by authors, 2025 after review of literature.

(a) (b) (c)

(d) (e) (f)

Figure 6. *Cont.*

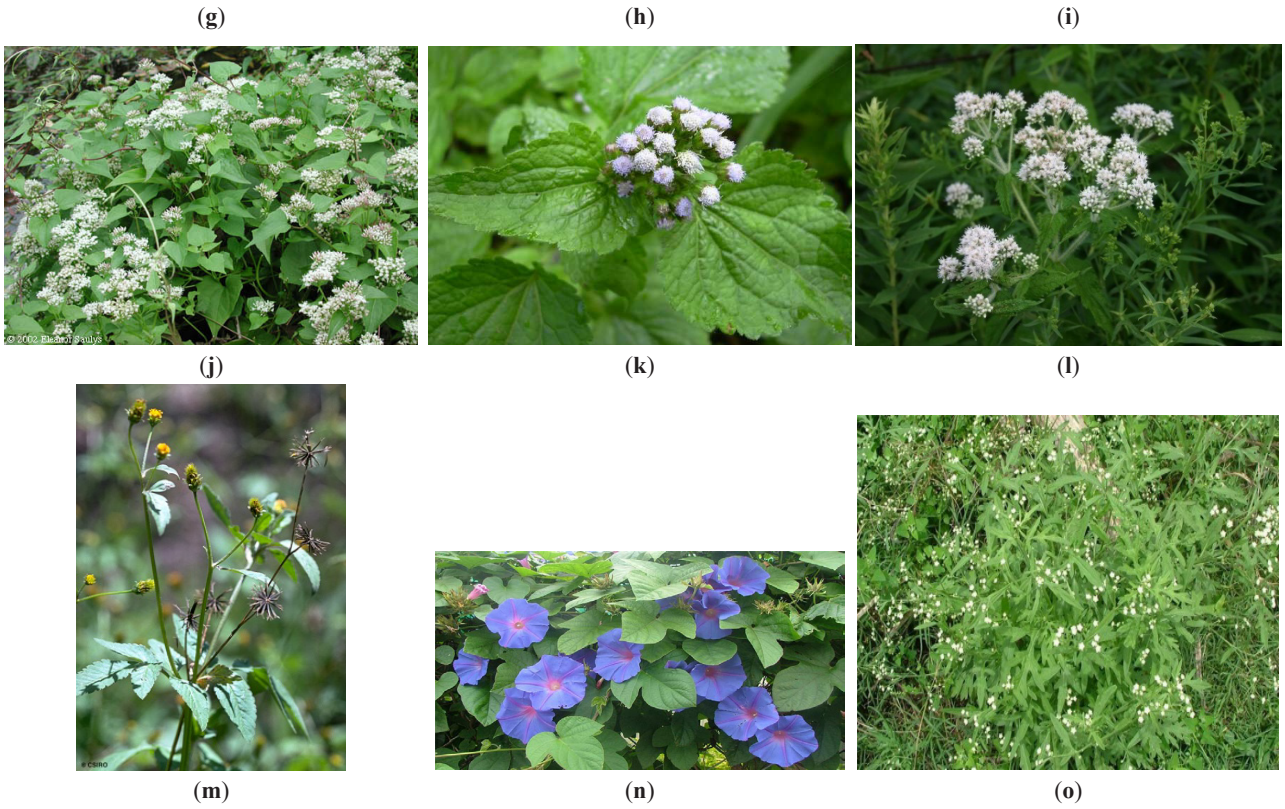


Figure 6. Anthropogenic threats to biodiversity in Sikkim Himalaya. (**a**–**c**) small, isolated patches of vegetation such as tree stands, roadside greenery, and vacant lots are replaced in Gangtok; (**d**–**f**) native tree species household construction, firewood collection in the suburban and rural habitats of sang, duga for timber; (**g**) Fodder collection at Mazitar; (**h**,**i**) pharmaceutical industries and hydro power projects at Mamring and Sirwani, East Sikkim; Invasive alien species—(**j**) *Eupatorium sp;* (**k**) *Mikania sp;* (**l**) *Ageratum conyzoides;* (**m**) *Bidens Pilosa;* (**n**) *Ipomoea sp;* (**o**) *Parthenium sp.*

The Sikkim Himalaya's biodiversity is increasingly threatened across multiple zones. Alpine and sub-alpine habitats face warming driven vegetation shifts that endanger endemic species; glacial and pro-glacial lakes are destabilized by glacier retreat and outburst-flood risk; Teesta river corridors are degraded by hydropower, flow alteration, and landslides; rhododendron and montane forests suffer from tourism pressure, land-use change, and invasive species; and lower-elevation agro-forest areas are fragmented by settlement growth, roads, and intensive farming. These converging pressures call for integrated, climate-sensitive conservation and land-use planning.

4. Conclusion

Urbanization in the Sikkim Himalaya (1991–2025) is fragmenting habitats and accelerating biodiversity loss through deforestation, infrastructure expansion, unregulated tourism, invasive species, and hydropower projects. Existing policies such as Sikkim Biodiversity Action Plan (2002), State Green Mission (2006), Eco-Sensitive Zones (2014) and *Mero Rukh Mero Santati* (2023) provide a framework for biodiversity conservation in the study area; however, weak enforcement, limited community participation, and implementation gaps reduce their effectiveness. In addition, climate change, erosion of traditional knowledge, and insufficient biodiversity monitoring further heighten ecological vulnerability. Priority actions include integrating biodiversity into urban planning with ecological corridors and green spaces; strengthening governance and enforcement; empowering communities via People's Biodiversity Registers and community-based conservation; controlling invasive species; promoting sustainable, low-impact tourism; and supporting research and long-term monitoring to guide adaptive management. These measures can align urban development with ecological

resilience, safeguarding Sikkim's unique biodiversity, ecosystem services, and sustainable livelihoods.

5. Future Research Directions

Future research in the Sikkim Himalaya should prioritize long-term biodiversity monitoring and high-resolution land-use datasets to capture ecological change over time. Studies are needed to disentangle the impacts of urbanization drivers such as hydropower, roads, and mining, while also examining thresholds of ecological resilience. Research should also explore how urbanization interacts with climate change to create compounded pressures on fragile mountain ecosystems. In parallel, policy analyses and governance studies can identify strategies that balance development with conservation, while livelihood-focused research can illuminate the socio-economic consequences of ecological change and ensure conservation planning remains equitable and locally relevant. Collectively, these directions will support evidence-based strategies to reconcile urban growth with biodiversity conservation in this critical Global Biodiversity Hotspot.

Author Contributions

S.S. was responsible for developing the conceptual framework of the topic, structuring the manuscript, drafting the outline and revising the final document. A.K.A. contributed in conducting the systematic literature review of the manuscript. All authors contributed critically to the draft and gave final approval for publication.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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