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Cover Image: A herd of Asian Elephant (*Elephas maximus*) in Corbett National Park, Uttarakhand, India. © Saket Badola

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Content

Editorial

1. *Conserving the Asian Elephant: Ecological, behavioural, and cultural imperatives*
Sanjeeta Sharma Pokharel, Honnavalli N. Kumara, M. Ananda Kumar 93

Commentaries

2. *Three Decades of Project Elephant: Conservation Efforts for Sustaining Asian Elephants in India*
Ramesh Kumar Pandey, Satya Prakash Yadav, Gobind Sagar Bhardwaj, Dheeraj Mittal, Aju Mathew George,
Gaurav Sirola, Anukul Nath, Parag Nigam, Bilal Habib 96
3. *Gaja-sastra: India's forgotten Elephant Science*
Ramesh Kumar Pandey..... 109

Research Articles

4. *Truncated Life: Patterns and Causes of Elephant Mortality in the state of Chhattisgarh, India*
Ramesh Kumar Pandey, Athira N G, Kalpana Roy, Ananya Dutta, Dheeraj Mittal, Parag Nigam, Anukul Nath,
Bilal Habib 115
5. *Navigating the coffee fields: elephants' use of habitat mosaics and the impacts of barriers on their spatial use of villages in a fragmented landscape of South India*
Deepak Bhat Dundi, Aditya Ghoshal, Nisar Ahamad, Nandini N C, Ganesh Raghunathan, M. Ananda Kumar..... 128
6. *Mortality investigations in wild Asiatic elephants (Elephas maximus) due to infected Kodo millet consumption in Bandhavgarh Tiger Reserve, Madhya Pradesh- A case study*
Vijay Kumar N. Ambade, Subharanjan Sen, Lakshman Krishnamoorthy, Ramesh Kumar Pandey, Amit Kumar Dubey, Anupam Sahay, Prakash Kumar Varma, Ritesh Sarothiya, Shoba Jawre, Nidhi Rajput, Aniruddha Majumdar, Tejas Karmarkar, Harikishan Sudini, Karikalan Mathesh, Swati Shrivastav, Nitin Gupta, Parag Nigam 139

Perspective

7. *Millet, Mycotoxins, and Megafauna: The Bandhavgarh Elephant Tragedy*
Anukul Nath, Ramesh Kumar Pandey, Parag Nigam, Bilal Habib 147

SUPPLEMENTARY

- Monograph**..... 152-201

Asian Elephants in central India: A detailed history (From the Earliest Times to 1947)
Raza Kazmi



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Conserving the Asian Elephant: Ecological, behavioural, and cultural imperatives

Sanjeeta Sharma Pokharel^{1,2} , Honnavalli N. Kumara³ , M. Ananda Kumar⁴

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Asian elephants (*Elephas maximus*) are ecologically, culturally, historically, and scientifically important across Asia, where they are revered in religious traditions, have long served important cultural roles, and continue to be a focus of scientific research and public interest. In the past five decades, Asian elephants have faced growing challenges due to rapid land-use changes and habitat fragmentation, leading to increasing incidences of human-elephant conflict and threatening their survival in both natural and anthropogenic habitats. As elephants in India are distributed across 33 elephant reserves, the management of elephant populations and their interactions with surrounding altered landscapes and people who share their land and resources has been a major conservation concern. Studies have shown that most of these negative interactions with humans adversely affect elephants' ecological, behavioural, and physiological status. The conservation and management of Asian elephants, particularly in India, home to the largest elephant population and among the highest human densities in Asia, demand a systematic and interdisciplinary approach that integrates ecological, behavioural, and cultural perspectives. As the demands placed on elephants and their habitats continue to evolve, so too must the frameworks, methodologies, and strategies we use to address these shifts.

Elephants in Ecological Processes

The Asian elephant holds disproportionate ecological and cultural significance within the Indian subcontinent, and its persistence is integral to maintaining forest ecosystem function, sustaining natural cycles, and preserving a heritage that spans millennia. As a recognised keystone species and ecosystem engineer, the Asian elephant exerts influence upon vegetation structure, seed dispersal dynamics, and faunal community composition that extends far beyond the scale of its population abundance. Empirical studies conducted across tropical forests in Asia have demonstrated that the presence of Asian elephants is associated with more robust mammalian co-occurrence networks, higher overall mammal abundance, and particularly enhanced populations of ungulates and primates, indicating that elephants function as ecological facilitators whose decline could destabilise entire animal communities. Furthermore, elephants provide essential ecosystem services through selective foraging that modifies forest structure and composition, the creation of waterholes during dry seasons that sustain multiple taxa, and the dispersal of seeds over distances exceeding 60 kilometres, thereby promoting forest regeneration and above-ground carbon sequestration. Their dung constitutes a nutrient-rich medium that supports sapling establishment and sustains invertebrate communities, including dung beetles, which, in turn, contribute to complex trophic interactions within the forest floor ecosystem.

Elephants as agents of higher-order behavioural processes

Asian elephants demonstrate advanced cognitive abilities, including problem-solving, emotional intelligence, and complex social communication. They exhibit exceptional cooperation, empathy, and intricate interactions within their herds, showcasing skills like tool use and self-awareness. As their natural habitats become fragmented, elephants adapt to the challenges in human-altered habitats, illustrating their capacity for risk assessment and survival. Each elephant possesses a unique personality, reflecting individual intelligence and judgment. Hence, conserving their habitats is crucial to ensuring the continuation of these remarkable traits and abilities, underscoring the importance of supporting their conservation.

Current conservation strategies for Asian elephants primarily derive from studies conducted in protected areas with limited human impact. However, many elephants now live in human-altered habitats, facing various degrees of anthropogenic challenges. Research shows that elephants exhibit significant behavioural plasticity, adjusting their movements, habitat use, social structures, and decision-making in response to these new conditions. Additionally, individual differences in how elephants respond to human pressures complicate conservation efforts, revealing gaps in existing strategies. To promote human-elephant coexistence and the effectiveness of conservation initiatives, policies must reflect contemporary ecological realities and acknowledge elephants' behavioural adaptations to human interactions. A context-dependent understanding of these dynamics is essential for formulating effective strategies that benefit both elephant populations and local communities.

Elephants reflect Asian cultural and historical significance

In the Indian context, the Asian elephant holds unparalleled cultural and historical importance, deeply embedded in religious, artistic, and political traditions. India shelters approximately sixty per cent of the global wild elephant population and approximately twenty per cent of the captive population in Asia. For many Indians, the elephant symbolises the national ethos to a degree that surpasses its formal designation as a protected species. Evidence of human-elephant associations dates back to the Indus Valley Civilisation, with seals from 2500–1500 B.C. suggesting domestication and management of elephants. Vedic literature contains numerous references to trained elephants. The elephant-headed deity Ganesha continues to confer cultural tolerance among Hindu communities, and depictions of elephants in Buddhist, Hindu, and Jain art, as well as on Harappan seals, attest to their enduring symbolic role as emblems of wisdom, power, and sensuality within Indian civilisation.

Elephants in Anthropocene

Asian elephants in India face severe threats from human activities, resulting in a significant decline in the viability of their habitats. Since the early 20th century, habitat loss and fragmentation from agricultural expansion and infrastructure development have reduced their range by approximately 78%. This has intensified human-elephant conflicts, leading to around 600 human fatalities annually and a conservation estimate of 100 elephant deaths due to retaliatory killings every year. Between 2009 and 2025, anthropogenic causes accounted for around 1,650 elephant deaths, primarily from electrocution, railway collisions, and poaching. Despite calls to manage contiguous populations, many elephants inhabit small, fragmented areas within human-dominated landscapes, exacerbating their vulnerability. Movement corridors often become bottlenecks due to agricultural and urban encroachment, creating ecological traps that hinder gene flow and increase mortality risk in fragmented populations.

Human and elephant management policies: Historical and contemporary views

Elephant management in India dates back to the Mauryan period (321–185 BCE) with Kautilya's *Arthashastra*, establishing protective policies. It was the basis for modern management policy in India, which led to the development of the "Elephant Preservation Act in 1879 to curb the killing of elephants in the country. After independence, the Indian Wildlife (Protection)

Act, 1972 provided the highest level of protection for elephants in India. Later, several national and state-level plans were developed and implemented. These include the "National Elephant Conservation Action Plan" in 1999, which outlined a comprehensive strategy for protecting the elephants through 16 "Elephant Reserves", protecting corridors and mitigating conflict, strengthening anti-poaching measures and promoting habitat restoration. Protection of elephants in the "Elephant Reserve" was expanded to a landscape-level approach in the MoEFCC's 2010 "Gajha-Elephant Task Force Report." In 2017, the Project Elephant Division of the MoEFCC released the "Guidelines for Management of Human Elephant Conflict," which provided a comprehensive framework for managing human-elephant conflict through various preventive and reactive strategies. Later, the Ministry released the "Best Practices of Human-Elephant Conflict Management in India" in 2020, which provides details on available mitigation measures to contain and manage human-elephant conflict. The latter two documents were further refined and culminated in the "Guidelines for Human-Elephant Conflict Mitigation" in 2023, providing comprehensive guidelines for mitigating human-elephant conflict through a coexistence approach that addresses the drivers, prevention measures, and emergency and rapid response. Despite these efforts, conflicts persist, underscoring the need for a landscape-level approach that integrates site-specific strategies and a thorough understanding of conflict dynamics to achieve effective management of elephants and people in shared landscapes.

Conservation importance

The cumulative evidence indicates that conservation strategies for the Asian elephant must transcend species-level protection and adopt an ecosystem-based approach that safeguards landscape connectivity, restores degraded corridors, and integrates community engagement to mitigate conflict. Given that elephants serve as umbrella and indicator species whose loss would trigger cascading effects on biodiversity, carbon storage, and hydrological cycles, increased investment in corridor management, habitat improvement, and the regulation of linear infrastructure is essential to maintaining ecological resilience in contemporary India. Conservation planning that recognises the Asian elephant as both an ecological engineer and a cultural keystone is therefore imperative for securing the integrity of India's forest ecosystems and upholding a natural heritage inseparable from the nation's identity.

30 years of Asian elephant conservation: A special issue

This Special Issue in the *Journal of Wildlife Science* on 30 years of Asian elephant conservation presents a curated collection of research and perspectives on key developments in the field. This special collection aims to enhance elephant conservation through a multidimensional scientific approach while exploring the historical and cultural significance of elephants in India. The selected contributions provide insights and innovative solutions that connect theoretical research with practical applications.

The issue opens with an article detailing the concerted efforts of the Project Elephant Division within the Ministry of Environment, Forests, and Climate Change (MoEFCC) of the Government of India over the past 30 years. The authors identify 150 elephant corridors and establish management guidelines for elephant conservation. While stressing the importance of robust legal frameworks, the article highlights that inadequacies in corridor protection, state-level implementation, and community involvement undermine the effectiveness of these policies. The paper advocates for the statutory recognition of elephant

corridors, enhanced integration of climate change adaptation strategies, and the implementation of inclusive governance models as essential measures to ensure the long-term survival of elephants in India.

The next article highlights the contributions of *Gaja-sastra*, an ancient Indian discipline centred on the management of elephants. It illustrates how scholars from the 3rd century BC developed a comprehensive understanding of elephant behaviour, medicine, and management through meticulous observation and practical experience. By revisiting these indigenous knowledge systems, the piece emphasises their relevance in addressing contemporary challenges, such as human-elephant conflict and conservation, while offering insights into ethical coexistence and culturally rooted conservation practices in India.

The prevalence of human-elephant conflict presents a formidable challenge for government agencies, local communities, and scientific and conservation organisations. These stakeholders must develop context-specific measures and management strategies to minimise conflict and foster coexistence in the shared landscapes. Retaliatory killings of elephants, driven by the intensifying conflict between human populations and elephants, represent a critical concern that necessitates a thorough understanding of the spatial and temporal patterns of elephant mortality.

A subsequent paper delves into the specific ecological factors contributing to elephant deaths in Chhattisgarh, identified as a hotspot for human-elephant conflict in India.

The dynamics of human-elephant relationships in shared landscapes have been increasingly affected by human development, driven by significant alterations to natural habitats. One of the studies in this issue investigates how elephants navigate human-dominated forest-plantation mosaics, highlighting their habitat use patterns across natural and anthropogenic habitats. This research underscores the challenges posed by physical barriers that confined elephant herds to a limited number of villages within a coffee-dominated landscape in South India.

Another important article examines the implications of Kodo millet consumption, which includes post-mortem investigations to ascertain the causes of elephant mortality at the wildlife-agriculture interface within the Bandhavgarh Tiger Reserve. Following this, the last study discusses the adverse effects of consuming Kodo millet infected with fungi, emphasising the presence of mycotoxins and their role in elephant fatalities in these regions. To mitigate these issues, the paper advocates a holistic approach that includes enhancing elephant movement corridors, improving agricultural safety, and implementing better crop management practices. It also emphasises integrating wildlife health considerations into landscape-level planning to avert such tragic incidents in Central India.

Additionally, a comprehensive monograph outlines the historical distribution of elephants and their gradual decline due to mass capture and habitat loss, which have led to significant population declines in central Indian states, including Chhattisgarh, Madhya Pradesh, and parts of Gujarat and Maharashtra. The recent reoccupation of some of these areas by elephants underscores the urgent need for proactive management strategies to resolve conflicts and promote elephant mobility, reinforcing the importance of dynamic conservation efforts in these regions.

This Special Issue emphasises the importance of a scientifically grounded approach to understand elephants, their needs, and their interactions with habitats and people. Such an understanding is vital for ecosystem health, human well-being, and the development of inclusive policies to conserve India's

National Heritage animal. We hope this collection serves as a valuable resource for researchers, practitioners, and policymakers, encouraging further dialogue and collaboration.

We extend our sincere gratitude to the contributing authors for their rigorous work and to the peer reviewers for dedicating their time to upholding the highest academic standards for this issue. We invite you to explore the articles in this collection and engage in the ongoing conversation.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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Three Decades of Project Elephant: Conservation Efforts for Sustaining Asian Elephants in India

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Abstract

The Asian elephant (*Elephas maximus*), a keystone species, plays a crucial role in maintaining ecological balance. It is distributed in Southeast Asia, with most of its population residing in India. Habitat degradation and fragmentation due to unplanned land-use changes, especially linear infrastructure, and human-induced mortality are viewed as major challenges for the conservation of this species. Thus, the Government of India launched Project Elephant in 1992, focusing on habitat conservation, human-elephant conflict (HEC) management, and the welfare of captive elephants. Over the past three decades, efforts under the aegis of Project Elephant (PE) have stabilised wild elephant populations through a landscape-based conservation approach. Key initiatives under the project include the establishment of 33 Elephant Reserves, identification and verification of 150 elephant corridors, and strengthening of applied science leading to the formulation of guidelines, advisories, and regulations to conserve both wild and captive elephant populations. In addition, training workshops, stakeholder collaboration, and technical reports have provided an impetus for capacity building and institutional responses. As HEC remains a pressing challenge, efforts have been made to foster positive community perceptions through awareness programs, increased ex-gratia compensation under the Centrally Sponsored Scheme Project Tiger & Elephant (CSS-PT & E Scheme), and annual Elephant Day celebrations. To acknowledge and motivate the relentless efforts of conservationists and frontline workers, the Gaj Gaurav Award was introduced in 2022, marking a significant milestone in PE journey. Through a multifaceted approach integrating policy, conservation strategies, community engagement, and international collaboration, PE has played a pivotal role in safeguarding India's elephants and their habitats. This paper provides an overview of the achievements and challenges of PE over the past three decades, offering insights into strengthening conservation efforts for the long-term survival of the Asian elephant.

Keywords: Elephant habitats, habitat fragmentation, human-elephant conflict, landscape-level approach, policy framework, wildlife protection.

Introduction

The Asian elephant (*Elephas maximus*) is a keystone species in tropical forest ecosystems, playing a vital role in seed dispersal, nutrient cycling, and vegetation dynamics (Fernando & Leimgruber, 2011). As ecosystem engineers, elephants shape forest landscapes, influencing broader ecological communities. Their large home ranges and habitat requirements position them as umbrella species, ensuring the conservation of a wide array of species (Albert *et al.*, 2018). Furthermore, their cultural and religious significance has established them as flagship species for conservation. Conserving elephants is not only essential for the survival of the species but also for maintaining the ecological integrity of tropical forests (Daniel, 1998).

Among the 13 Asian elephant range countries, India harbours more than 60% of the global population, distributed across four regional landscapes: Northwest, Northeast, East-Central, and Southern India (Pandey *et al.*, 2024a). Although India has managed to maintain a relatively stable elephant population, the species has suffered a significant range contraction across Asia in the last few decades (Pandey *et al.*, 2024b). Historically, elephants roamed from the Tigris-Euphrates River Basin in the west to the Yangtze River Basin in the east. However, habitat loss, fragmentation, and poaching have reduced their range to 5–7% of their historical extent, with local

extinctions in several countries (MoEFCC, 2022). Even in large nations such as China, where elephants were once widespread, fewer than 300 individuals remain today (Zhang *et al.*, 2024).

Given that India harbours more than 60% of the global Asian elephant population, ensuring its long-term persistence within a densely populated and rapidly developing landscape presents a unique conservation challenge. Despite India's cultural reverence for elephants, conservation challenges have become increasingly prominent since the late 20th century. During the 1970s to 1990s, rampant poaching for ivory, particularly targeting bull elephants, led to severely skewed sex ratios in populations, threatening long-term genetic viability. For instance, in the Periyar Tiger Reserve in Kerala, the male-to-female ratio dropped to an alarming 1:100 during the 1990s (Sukumar *et al.*, 1998). Simultaneously, human-elephant conflict has escalated due to habitat encroachment, leading to significant economic losses, human casualties, and retaliatory killings. Such conflicts erode local support for conservation efforts, necessitating urgent and strategic interventions. Recognising these pressing threats, the Indian Government launched Project Elephant (PE) in 1992 as a dedicated national conservation initiative for elephant. Administered by the Ministry of Environment, Forest and Climate Change (MoEFCC), the project aims to ensure the long-term survival of wild and captive elephant populations by addressing key threats such as habitat degradation, human-elephant conflict, and poaching. Project Elephant collaborates with the state forest departments and technical institutions to achieve its objectives.

This paper synthesizes published datasets, government records, and peer-reviewed literature to critically evaluate the long-term conservation outcomes of Project Elephant (PE). By examining three decades of implementation, the study assesses the programme's effectiveness in securing elephant populations and habitats, mitigating human-elephant conflict, and strengthening conservation governance. The review further identifies persistent challenges, emerging threats, and strategic priorities to enhance the future trajectory of elephant conservation in India.

Conservation interventions implemented under Project Elephant

Core focus

Project Elephant (PE) is a comprehensive conservation initiative by the Government of India aimed at ensuring the long-term survival of wild and captive elephants. The project focuses on protecting and restoring elephant habitats to sustain viable populations while implementing measures to mitigate human-elephant conflicts and promote coexistence. Strengthening anti-poaching strategies and curbing the illegal trade of elephant body parts are key priorities for safeguarding elephants. Additionally, PE emphasises ethical management and the welfare of captive elephants, ensuring improved living conditions. Scientific research and monitoring play crucial roles in understanding elephant ecology, population dynamics, and behaviour, contributing to more effective conservation strategies. Furthermore, the initiative actively engages local communities through education and outreach, fostering awareness and participation in conservation efforts.

Institutional framework

The MoEFCC administers PE and implements it through a collaborative approach involving multiple agencies. State forest departments play a crucial role in on-ground conservation and management efforts, ensuring the protection of elephant habitats and populations. The Wildlife Institute of India (WII) has contributed by conducting research and providing technical expertise to enhance conservation strategies (PE-WII-MoEFCC, 2024). The Central Zoo Authority (CZA) oversees the welfare and ethical management of captive elephants to ensure their

well-being. Additionally, the National Tiger Conservation Authority (NTCA) collaborates on habitat protection and policymaking, reinforcing the holistic approach to elephant conservation in India. The Wildlife Crime Control Bureau (WCCB) plays a crucial role in elephant conservation by combating the illegal wildlife trade, preventing poaching, and dismantling organised wildlife crime networks.

Committees under the aegis of Project Elephant

The PE has a Steering Committee, chaired by the Hon'ble Minister of MoEFCC, which includes State Chief Wildlife Wardens, scientists, and experts outside of the government agencies. This committee regularly identifies and discusses key issues related to elephant conservation in India. Between 1992 and 2025, there were 21 meetings of the steering committee, with all topics and decisions carefully recorded. To tackle the evolving challenges, the Central Project Elephant Management Committee (CPEMC) was established on 28 December 2018, bringing together experts and officials for focused oversight. The CPEMC monitors the adherence to and implementation of directives and court orders regarding elephant conservation. Additionally, on 22 August 2019, the Captive Elephant Health Care and Welfare Committee (CEHWC) was constituted to improve the health and welfare of captive elephants across the country.

Population status and habitat conservation

Population trends, census methods and distribution

In India, Asian elephants are mainly distributed across the southern, northeastern, east-central, and northern regions (Figure 1). Accurate data on population parameters, such as distribution and abundance, are essential for the effective management of elephant populations (Pandey *et al.*, 2024a). Historical estimates of wild elephant abundance are largely unavailable. However, contemporary accounts provide indirect evidence of their former numbers and distribution. Pyrard de Laval, a French navigator who travelled in India during the reign of Emperor Jahangir in the early seventeenth century, recorded approximately 40,000 elephants within the Mughal Empire and Bengal, a figure that likely encompassed both captive and free-ranging individuals (Sukumar, 2011). This account underscores the historical prominence of elephants across the Indian subcontinent.

The earliest known effort to estimate India's elephant population was conducted by F. W. Champion in 1929 in the forests of the erstwhile United Provinces (now Uttar Pradesh and Uttarakhand). This was followed by population assessments carried out by the Uttar Pradesh Forest Department in 1966–67, with subsequent surveys in 1976 and 1978, marking the beginning of systematic elephant population monitoring in the country (Daniel, 1980).

Between 1978 and 1980, regional elephant population assessments undertaken in the Northeastern, Northern, East-Central, and Southern landscapes were synthesized to generate the first nationwide estimate of India's elephant population. Based on total count surveys, the population was estimated at approximately 19,558 elephants, providing an important baseline for subsequent conservation planning and monitoring efforts (Lahiri-Choudhury, 1980; Singh, 1978; Shahi, 1980; Nair *et al.*, 1980).

Following the launch of Project Elephant in 1992, elephant population assessments were conducted at approximately five-year intervals using a range of methods, including total counts, registration counts, waterhole counts, transect surveys, dung counts, and other site-specific approaches. Based on these surveys, India's elephant population was estimated at 25,604 in 1993, 25,877 in 1997, 26,413 in 2002 and 27,694 during 2007–08, indicating a gradual increase in elephant numbers over this period.

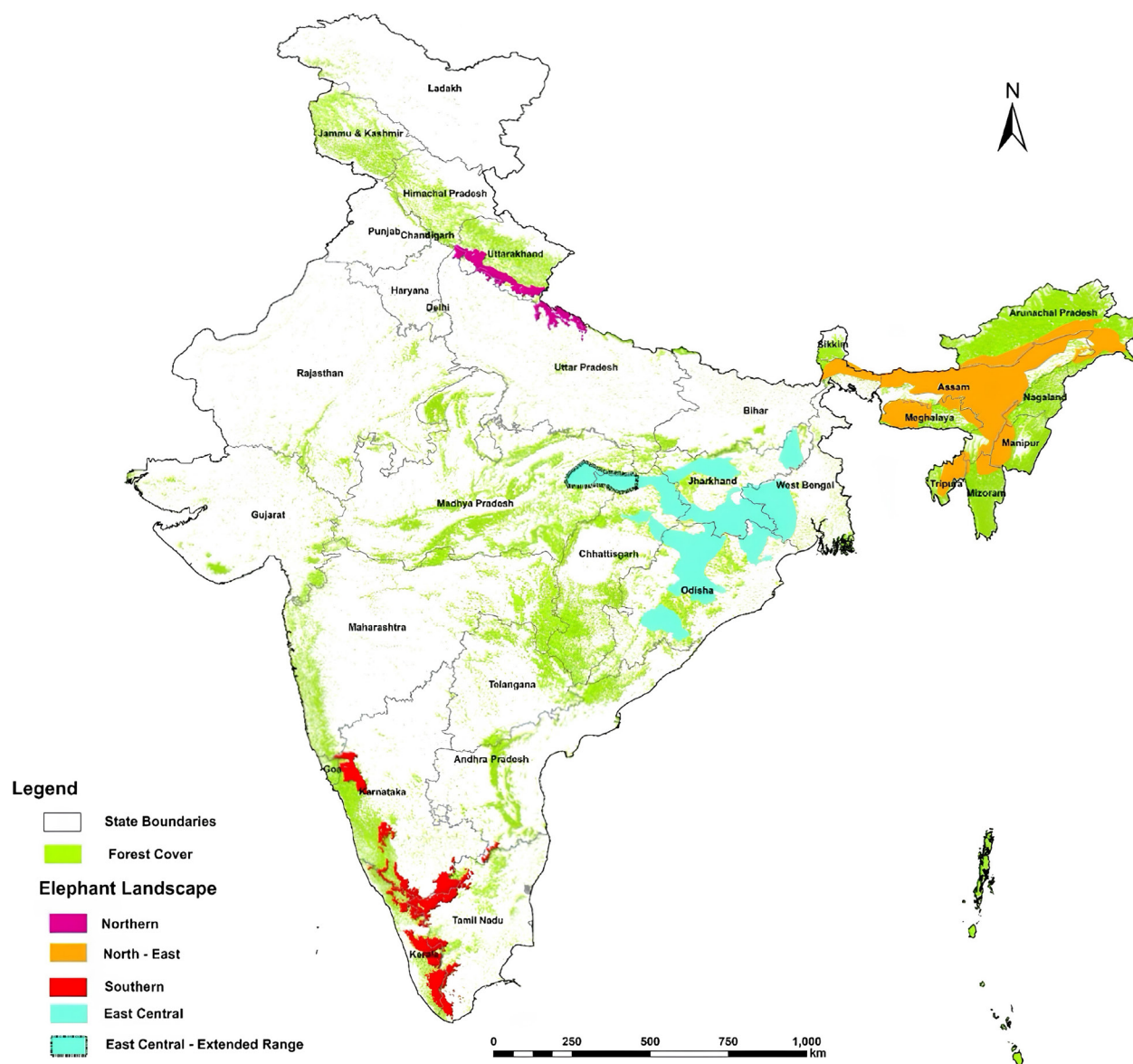


Figure 1. Major elephant landscapes of India and associated forest cover, illustrating the current distribution of elephants and areas of recent range expansion beyond their historically recognized range.

Project Elephant revised its elephant population estimation protocol in 2005, introducing synchronized surveys across all major elephant landscapes in the country. The first nationwide synchronized estimate was conducted in 2005, and the final assessment using this methodology was carried out in 2017, yielding an estimated population of 29,964 elephants (MoEFCC, 2017). The increase from 27,694 elephants in 2007–08 to 29,964 in 2017 reflects population stability rather than substantial growth. In the context of ongoing habitat fragmentation and anthropogenic pressures across elephant range states, the maintenance of a stable population underscores the role of Project Elephant as a persistence-oriented conservation programme, focused on preventing population decline and securing long-term viability (Figure 2).

In 2022, elephant population estimation was integrated into the All-India Tiger and Co-predator Assessment, marking a major methodological advancement through the adoption of DNA-based genetic mark-recapture techniques using dung samples. This approach overcame key limitations of traditional direct and indirect count methods, providing the first robust,

landscape-scale estimate of India's wild Asian elephant population at 22,446 individuals (95% CI: 18,255–26,645). Karnataka supported the largest population (6,013), followed by Tamil Nadu (3,136) and Kerala (2,785), while the Western Ghats and the North-Eastern Hills–Brahmaputra landscapes emerged as the country's principal elephant strongholds (Qureshi *et al.*, 2025) (Figure 3).

Growth of elephant reserves

Since PE was started in 1992, the idea of a "landscape approach" to elephant conservation has been highlighted because of the wide ranging behaviour of elephants. Considering this, the concept of Elephant Reserves (ER) was introduced, which serves as a management unit and includes forests and regions well outside of Protected Areas (PAs). Protected areas in India cover less than 40% of the elephant range. Elephant conservation cannot be ensured in the long run by concentrating only on PAs. Unlike tiger reserves, which are managed mainly by the forest department, elephant reserves require coordination with other ministries, agencies, and local communities. India has notified 33 Elephant Reserves (Figure 4) across 14 states covering an

area of 80,777 km² ($\pm$ 2,564.85 SD, range = 23.5 –13440 km²). Singphan ER (23.5 km²) in Nagaland is the smallest ER in India, whereas Singbhum (13,440 km²) in Jharkhand is the largest. Approximately 27,372.17 km² area of ERs overlaps with of the

130 existing PAs, and accounting for 15% of the total PA area in the country. Further, a total of 33 ERs overlap with 25 Tiger Reserves (TRs) across nine states of the country (Pandey *et al.*, 2025c). Tiger Reserves are statutory management units for

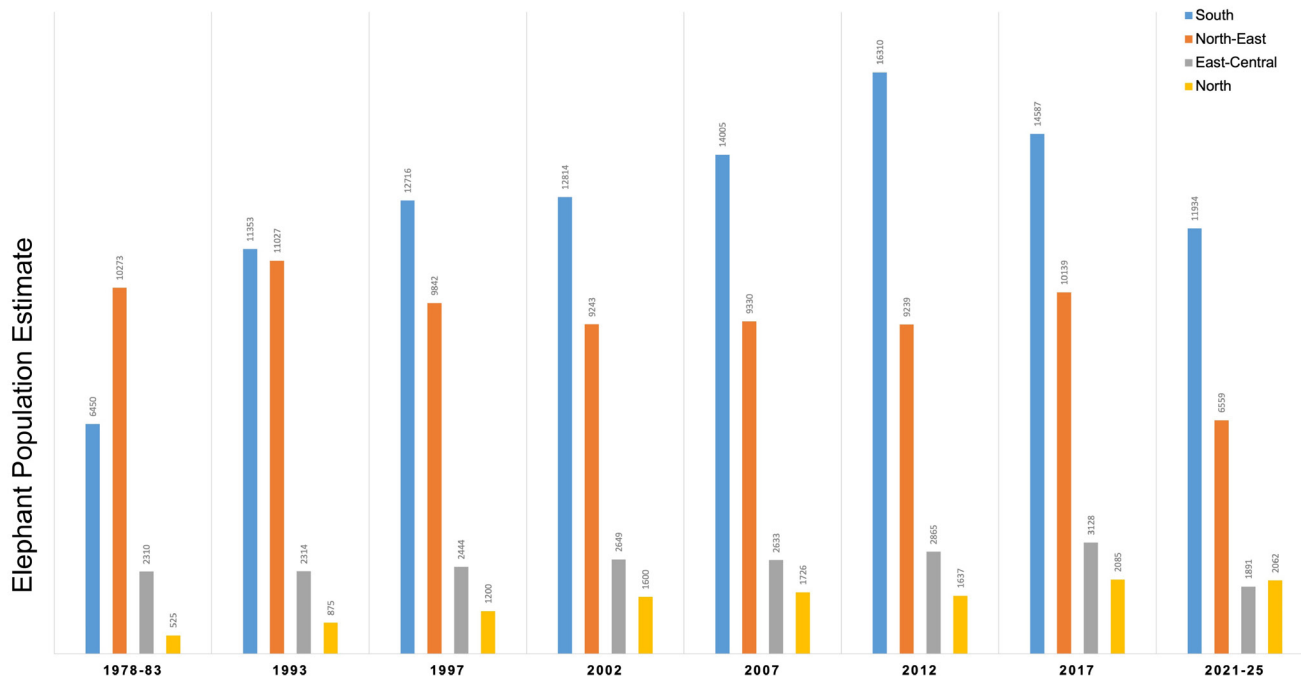


Figure 2. Trends in elephant population estimates across the four major elephant landscapes of India from 1978 to 2021–25. Estimates up to 2007 were derived primarily from total count surveys, while the 2012 and 2017 assessments employed a combination of total counts, dung-count methods, and sample block counts. The 2021–25 estimates were generated using DNA-based genetic mark–recapture analyses within a Spatially Explicit Capture–Recapture (SECR) framework. Owing to differences in survey methodologies, estimates from 2021–25 are not directly comparable with earlier assessments and should be considered a new baseline for future monitoring.

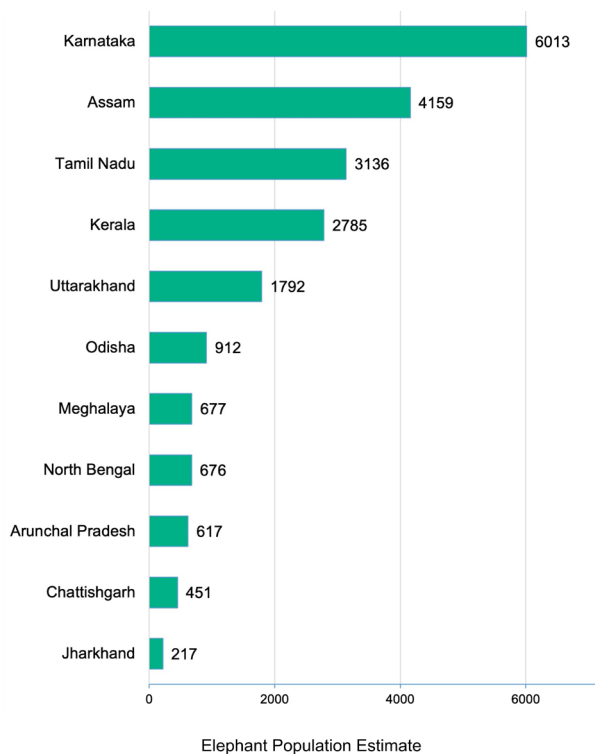


Figure 3. State-wise estimates of India's wild elephant population derived from the DNA-based Synchronised Assessment of India's Elephant Population (SAIEE 2021–25).

the protection and conservation of tigers in the country, as per the Wildlife (Protection) Act, 1972. The expansion of elephant reserves beyond protected areas reflects a shift from site-specific to landscape-level management. This demonstrates that elephant conservation in densely populated countries depends on multi-use landscapes rather than strictly protected wilderness areas.

Significance of Elephant Corridor

An elephant corridor is defined as the pathway that elephants use to move between habitat patches to fulfil basic life history requirements, including habitat-use within home range, seasonal migrations. Elephant corridor protection has long been viewed as an essential measure to protect elephants and reduce HEC in India. Corridors facilitate animal movement between habitat patches, thus maintaining the long-term demographic and genetic viability of elephant populations. The Gajah-Elephant Task Force report in 2010 enlisted 88 elephant corridors throughout India (Rangarajan *et al.*, 2010). In April 2022, during the 16th PE Steering Committee meeting, it was noted that there is a need to conduct ground validation of corridors, as the Gajah report was released 12 years ago. Given this, a team including representatives from the respective Forest Divisions of the SFDs and individuals designated by Project Elephant verified all the elephant corridors mentioned in the Gajah report and additionally suggested by the SFDs. In total, 150 elephant corridors were documented from 15 elephant range states in India's four elephant-bearing zones (PE - MoEFCC, 2023; Pandey *et al.*, 2024c). The highest number of elephant corridors ($n = 26$), which accounts for 17% of the total, is located in West Bengal. The east-central region has the most corridors (35%), followed by the northeast (32%), south (21%), and north (12%) (Figure 5). While 40% of the corridors showed increased

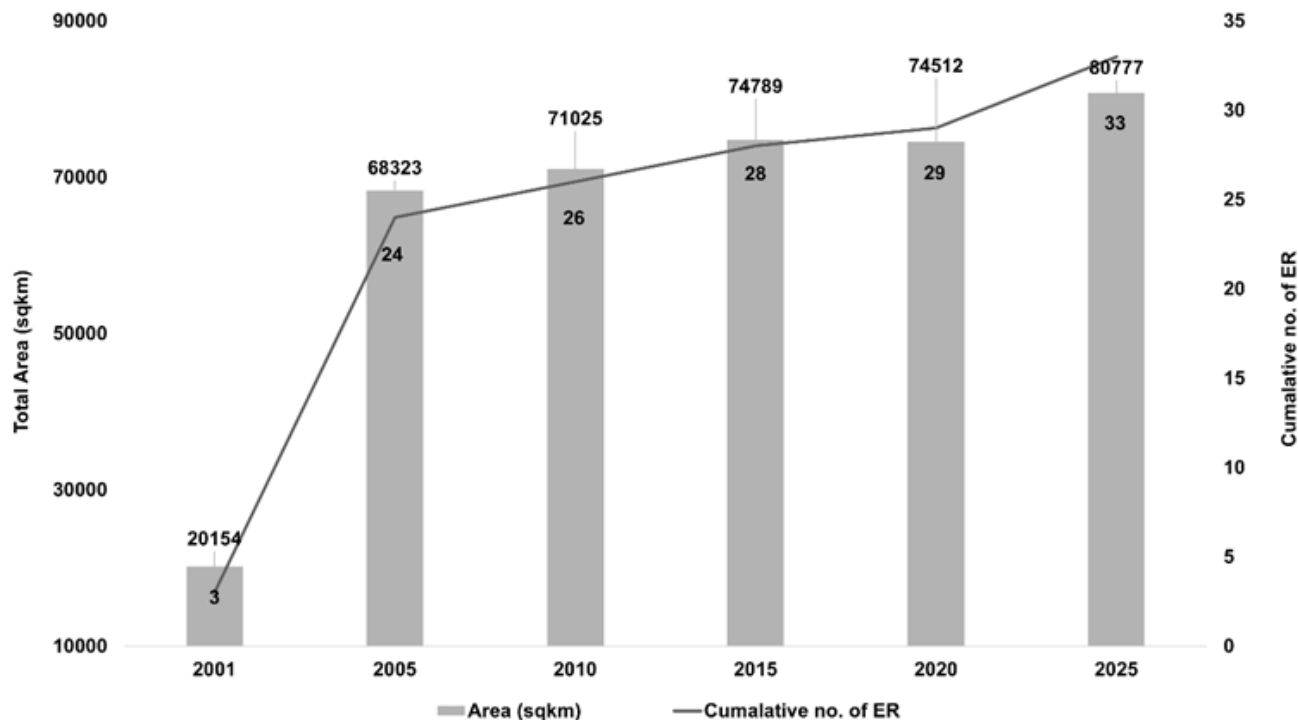


Figure 4. Growth in the number of Elephant Reserves (ERs) in India from 2000 to 2025, highlighting the progressive expansion of the protected network dedicated to elephant conservation and habitat management.

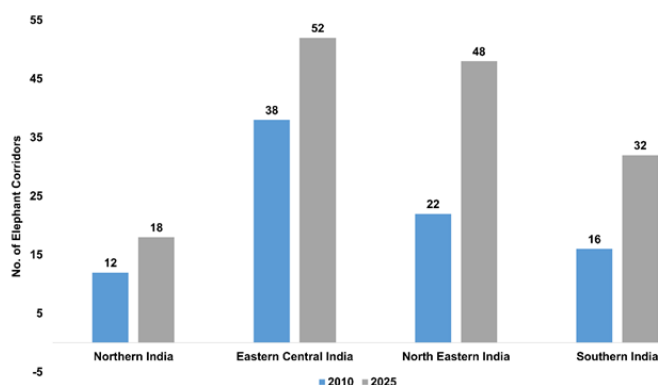


Figure 5. Region-wise increase in the number of identified elephant corridors in India between 2010 and 2025.

elephant movement, 10% are impaired and need restoration. Corridor validation and restoration indicate that functional connectivity is being maintained despite increasing infrastructure development, suggesting that connectivity management may be more critical than habitat expansion for long-term genetic viability of elephants in human-dominated landscapes.

Key conservation strategies & policy interventions

Addressing Human–Elephant Conflict (HEC)

In India, HEC results in the loss of over 500 humans and 100 elephants annually (Pandey *et al.*, 2024b). Given its impact on both elephant conservation and local livelihoods, the mitigation of this conflict is of utmost importance. The PE plays a key role in addressing these challenges by bridging knowledge gaps through resource materials, stakeholder consultations, and close engagement with the SFDs in the elephant range states.

Regular training programs are conducted for forest officials, covering various conflict-mitigation strategies. Additionally, best practices for managing HEC are periodically reviewed and published. Recently, with technical assistance from the WII and WWF-India, PE developed a user-friendly “Field Manual for Managing HECs in India”, available in multiple regional languages (Hindi, Assamese, Odia, Malayalam, Kannada, and Tamil), providing on-ground officials with quick-reference guidance (PE-MOEFCC, WII & WWF, 2022). The project also supports research aimed at identifying human–elephant conflict (HEC) hotspots and the underlying drivers of conflict. Recent studies from Assam, Chhattisgarh, and Jharkhand have provided comprehensive insights into the spatial and temporal patterns of HEC over the past two decades, generating critical evidence to guide targeted mitigation and management interventions (Habib *et al.*, 2025a,b,c; Roy *et al.*, 2025a, b; Pandey *et al.*, 2025a,b; Pandey *et al.*, 2026; Athira, *et al.*, 2026).

Recognising that long-term conflict resolution takes time, immediate measures to minimise losses are crucial, particularly for marginal farmers. To support them, PE has been working to enhance ex-gratia compensation for those affected by elephant-related damage. In a significant step, crop losses due to wild animals are now covered under the Pradhan Mantri Fasal Bima Yojana (PMFBY), a national crop insurance scheme.

Project Elephant and Project Tiger were two sub-schemes under the Integrated Development of Wildlife Habitats (IDWH). Following approval from the Expenditure Finance Committee (EFC) and the Cabinet, the schemes were merged for better resource allocation, synergy, and a focused conservation approach. States now submit a single Annual Plan of Operations (APO), streamlining financial assistance and project execution. The merged scheme is called CSS-Project Tiger and Elephant (PT&E), during 2023–2024, a total of Rs. 239.59 crores was disbursed for the conservation of Tigers and Elephants under this scheme.

Establishment of the Elephant Cell

The Elephant Cell at the WII, Dehradun, was established as a technical wing of the PE Division to enhance elephant conservation efforts in India. Recommended by the Elephant Task Force (Gajah Report) and approved during the 13th Steering Committee meeting on PE (2014), the cell aims to address critical challenges, such as data management, human-elephant conflict, habitat protection, and capacity building. It strengthens efforts towards the conservation of elephants, both in the wild and in captivity. The Elephant Cell also conducts field-oriented training for PA managers and frontline staff posted in elephant reserves in India, enhancing their capacities to manage elephant populations, their habitats, and other associated concerns.

Advisory & Technical Reports

Project Elephant, in collaboration with various organisations, agencies, and ministries, has been at the forefront of developing a comprehensive set of guidelines, advisories, and rules aimed at enhancing the management of the conservation and welfare of captive elephants in India. These documents address a wide range of critical issues, including elephant healthcare, habitat conservation, human-elephant conflict mitigation, captive elephant welfare, and infrastructure-related risks, such as train accidents and power transmission lines. Several guidelines/advisories have been provided over the years, covering areas such as disease surveillance, post-mortem practices, and safety measures for power transmission and railway tracks (Table 1). Additionally, the introduction of protocols for DNA profiling of captive elephants reflects a commitment to ethical and scientific management of elephants. These advisories and guidelines are crucial for shaping national conservation policies, establishing a strong framework to protect elephants, promoting their welfare, and ensuring their long-term survival.

PE has published a range of technical documents, research reports, and articles to support elephant conservation in India. A quarterly newsletter, "Trumpet", is published by Elephant Cell under PE, providing regular updates in the field of elephant conservation in India.

Building on these efforts, several key knowledge products have been developed under Project Elephant to support evidence-based conservation and management. Best Practices of Human-Elephant Conflict Management in India (MoEFCC-WII, 2020) compiles field-tested interventions and state-level experiences for mitigating human-elephant conflict. The Field Manual for Managing Human-Elephant Conflict (PE-MoEFCC, WII & WWF-India, 2022) provides practical guidance for frontline staff and forest managers working in conflict-prone landscapes. The Elephant Corridors of India 2023 (PE-MoEFCC, 2023) identifies and maps critical corridors that facilitate landscape connectivity, a cornerstone of long-term elephant conservation. Complementing these publications, the Elephant Reserves of India: An Atlas and the two-volume Land-Use and Land-Cover Classification series (WII-PE-MoEFCC, 2022a,b,c, 2023) provide comprehensive spatial, ecological, and habitat information for all designated elephant reserves in India, thereby strengthening conservation planning and management.

Project Elephant has developed several standard operating procedures (SOPs), technical manuals, and management frameworks to strengthen elephant conservation and management. These include the Recommended Operating Procedure for Capture and Translocation of Elephants in Distress and Conflict Situations (PE-MoEFCC-WII, 2024a) and the Necropsy and Carcass Disposal SOP (PE-MoEFCC-WII, 2023c), which provide standardized guidance for field interventions, animal rescue, translocation, and mortality investigations. The Guidelines on Human-Elephant Conflict Management (GIZ & MoEFCC, 2023) and Caring for Elephants (Nigam *et al.*, 2022) further support effective conflict mitigation, humane handling, and improved welfare standards. In addition, the Management Effectiveness Evaluation (MEE) of Elephant Reserves in India provides a framework for assessing conservation performance, governance, and field implementation across elephant reserves (PE-MoEFCC-WII, 2023b, 2024b), while the Framework for Preparation of Elephant Conservation Plans (ECPs) offers standardized guidance for developing long-term, science-based conservation strategies (PE-WII-MoEFCC, 2024).

Table 1: Advisory guidelines and recommendations issued by Project Elephant and other agencies for the management and welfare of wild and captive elephants in India.

S. No.	Advisory/ Guidelines issued	Year
01	Techniques & Procedure for Post-Mortem of Elephants	2003
02	Guidelines for Care and Management of Captive Elephants	2008
03	Centrally Sponsored Scheme – Project Elephant Guidelines	2013
04	Guidelines for Facilitating Effective and Scientific Management of Zoos in India	2013
05	Standards/Norms for Recognition of Elephant Rehabilitation/Rescue Centers	2017
06	Guidelines for Management of Human-Elephant Conflicts	2017
07	Suggesting Eco-Friendly Measures to Mitigate Impacts of Power Transmission Lines	2019
08	Standard Operating Procedure (SOP) for Dealing with Captive and Wild Elephant Mortalities Due to Anthrax/Suspected Cases of Anthrax	2019
09	Standard Operating Procedure for Elephant Endotheliotropic Herpes Virus Hemorrhagic Disease, Reiteration	2021
10	Post-Mortem of Elephants by Panel of Three Veterinarians	2022
11	Advisory regarding the implementation of measures to mitigate the impact of power transmission lines and other power infrastructure on elephants and other wildlife.	2022
12	Advisory for DNA Profiling of Captive Elephants During Transit	2022
13	GIZ - MoEFCC Guidelines on HEC Management	2023
14	General Guidelines for Suggesting Mitigation Measures on Railway Tracks passing through Elephant Habitats in India	2023
15	Captive Elephant (Transfer or Transport) Rules, 2024	2024
16	Advisory on tusk trimming in captive elephants	2025
17	Measures suggested to mitigate elephant and other wildlife train collisions on vulnerable railway stretches in India.	2025
18	Healthy Feet, Healthy Elephants: A Guide to Foot Care in Captive Asian Elephants.	2025
19	Handbook on Elephant Intrusion Detection System of Indian Railways	2025

State-Specific Mitigation Reports and Conflict Reduction Studies

A major nationwide initiative in 2024 was the release of ten state-specific mitigation reports focusing on reducing elephant–train collisions on vulnerable railway tracks across Assam, Arunachal Pradesh, West Bengal, Odisha, Tamil Nadu, Uttarakhand, Karnataka, Madhya Pradesh, Nagaland, and Jharkhand (PE-MoEFCC-WII, 2024(c)–2024(i)). The consolidated report, including all 14 states (PE-MoEFCC-WII, 2025), was released during the 21st Steering Committee meeting of Project Elephant held on 26 June 2025. Additionally, comprehensive studies on understanding elephant conflict issues and suggesting conflict reduction measures were recently completed for the states of Assam, Chhattisgarh, and Jharkhand (Habib *et al.*, 2025a; Habib *et al.*, 2025b; Habib *et al.*, 2025c).

Welfare and management of captive elephants

Under the Wildlife (Protection) Act of 1972, both wild and captive elephants receive equal legal protection. Most captive elephants in India were either caught in the wild or born to wild-captured elephants, and the country has a long history of elephant capture and training. Currently, India has approximately 2,675 captive elephants, of which 1,821 are under private ownership. Ensuring the welfare and humane care of elephants remains a core mandate of the PE. Capacity-building and training programs are regularly organised for veterinarians and elephant handlers to improve captive elephant welfare. These sessions bring together forest veterinarians from across the country for hands-on training.

Gaj Soochana App

The PE, in collaboration with the WII, has developed the Gaj Soochana App to set up a database of captive elephants for the country. This Android-based DNA profiling application was developed exclusively for the State Forest Departments (SFDs), providing a secure platform to store vital information, such as the elephant's identity (name, microchip number, age, origin, and facility type), ownership details, body measurements, photographs, and veterinary records. This initiative creates a comprehensive genetic and physical database, facilitating the identification and monitoring of interstate transfers and preventing illegal trade. It may also act as a tool against illegal trade, strengthening conservation efforts. A database of over 1,000 captive elephants has already been created, and 70% of the sampling has been completed. Special forensic kits have been developed for DNA sampling, and the Ministry has made DNA profiling mandatory for Captive Elephant transportation through the Captive Elephant (Transfer or Transport) Rules, 2024.

Combatting illegal trade in elephant body parts

According to the Gajah report of 2010, despite India having approximately 30,000 elephants, the number of adult tuskers was estimated to be no more than 1,200. Illegal poaching of male elephants for ivory remains a serious threat to elephant populations worldwide. It is crucial to protect these large tuskers from ivory poaching. The peak of elephant poaching in India occurred during the 1980s and 1990s (Rangarajan *et al.*, 2010), and addressing this issue remains a complex challenge, requiring a strong intelligence network, sting operations, effective evidence gathering, and judicial support for prosecuting offenders. To enhance anti-poaching efforts, Project Elephant collaborates closely with the WCCB, SFDs, and other enforcement agencies. Structured workshops and training programs should focus on intelligence gathering, field patrolling, offender detection, and legal prosecution to strengthen wildlife protection measures.

Asian elephants have been listed in CITES Appendix I since 1975. Furthermore, the 2003 MIKE Programme (Monitoring the Illegal Killing of Elephants) was launched in South Asia, including India, under a mandate from the CITES COP Resolution 10.10. The program was designed to provide critical data on elephant poaching trends and support conservation efforts through

informed decision-making. In India, the MIKE Programme operates across ten designated sites, which includes Chirang-Ripu, Deomali, Dihing Patkai, Garo Hills, Eastern Dooars, Mayurbhanj, Shivalik, Nilgiri, Anamalai, and Periyar Elephant Reserves. Project Elephant provides data on elephant poaching and ivory seizures to MIKE and CITES every year.

Anti-poaching interventions appear to have shifted the primary threat from direct hunting to habitat-related mortality, indicating a transition in conservation challenges over time from exploitation pressure to landscape pressure.

Capacity building workshops and training programs

Project Elephant regularly conducts capacity-building workshops to sensitise key stakeholders, including Railway and Electricity Board officials, distribution agencies & companies, Park Managers, and Elephant Handlers, to mitigate human–elephant conflicts and ensure wildlife safety. The workshops are directed towards reducing railway-induced elephant mortality, preventing electrocution through safer power infrastructure, and enhancing the management of elephant reserves. Special training is also provided to elephant custodians and handlers for the welfare of captive elephants through improved care. Through the introduction of new advances and technologies, workshops facilitate the adoption of wildlife-friendly infrastructure and conservation practices by stakeholders, promoting a more sustainable coexistence of human activities and elephant habitats. During the period 2019–2025, these workshops trained over 370 officials from the Railways, Power Ministry, Forest Department, and other stakeholders.

Awareness and recognition

Elephant as India's National Heritage Animal

India's recognition of the elephant as its National Heritage Animal in 2010 marked a significant step toward prioritising the conservation of elephants. This declaration acknowledged the elephant's cultural and ecological importance and underscored the need to protect this majestic species. By granting the elephant this status, India aimed to promote widespread awareness of the challenges faced by elephants, such as habitat loss, poaching, and human–elephant conflict. This decision brought national attention to elephant protection, laying the groundwork for various conservation initiatives.

World Elephant Day observance & Gaj Gaurav Award

Launched in 2012, World Elephant Day, one of the prominent conservation initiatives, is observed globally every year on 12 August to raise awareness about elephant conservation. India has played a central role in this observance, with initiatives such as the Gaj Gaurav Award, launched in 2022, to recognise the contributions of captive elephant owners and those working on the frontlines of elephant welfare. This award honours the exceptional work of forest officers, private custodians, and other stakeholders committed to the care and conservation of elephants. As part of its ongoing commitment to elephant conservation, PE completed 30 years in 2022. To celebrate this achievement, the MoEFCC, in collaboration with the Government of Assam, organised Gaj Utsav 2023 at Kaziranga National Park. Held on April 7–8, 2023, the event was inaugurated by the President of India and brought together policymakers, scientists, forest officials, and conservationists to discuss the challenges and future directions for elephant conservation in India. This event highlighted India's dedication to safeguarding elephants and reaffirmed the country's political will to support conservation initiatives.

Political Will, Technological Advancements, and Future Conservation Needs

The Indian government's support for elephant conservation is reflected not only through policy interventions such as the Wildlife (Protection) Act, 1972, but also through the implementation of modern conservation strategies. The use of cutting-edge technologies such as GPS tracking, drones, and mobile applications plays a critical role in monitoring elephant populations, tracking migration patterns, and preventing poaching. These advancements are vital for safeguarding elephants in an increasingly human-dominated environment. However, the future of elephant conservation relies on continued investment in habitat conservation, reducing human-elephant conflicts, and strengthening anti-poaching efforts. These steps are essential for the long-term survival of the species.

Awareness Programs and Community Engagement

Awareness programs across India play a vital role in promoting elephant conservation and actively involve communities and youth in these efforts. As part of this initiative, every year, Elephant Day is celebrated to raise awareness and sensitise the masses towards elephant conservation. A notable example is World Elephant Day 2024, featuring a nationwide campaign reaching 10 lakh children across 5,000 schools, focusing on the pressing issue of HEC. Such initiatives are essential for educating the next generation about the importance of elephant protection and conflict mitigation. These large-scale campaigns highlight the significance of community participation and public engagement in the collective mission to safeguard India's National Heritage Animal.

International collaboration in elephant conservation

India's commitment to elephant conservation at the global level is also evident in its active participation in international collaborations. PE works closely with key global organisations, including the IUCN Asian Elephant Specialist Group, which provides scientific expertise and guidance on Asian elephant conservation. India collaborates with neighbouring countries to promote transboundary elephant conservation, acknowledging the need for coordinated efforts across borders to protect migratory elephant populations. In a significant step toward regional cooperation, India and Bangladesh signed a protocol on transboundary elephant conservation on 17th December 2020, marking a crucial moment for cross-border collaboration for the protection of elephants in South Asia. India actively participated in the 3rd and 4th Asian Elephant Range States Meetings held in Kathmandu, Nepal, and Siem Reap, Cambodia, respectively.

Conservation effectiveness of Project Elephant

The outcomes indicate that Project Elephant has functioned less as a classical species recovery programme and more as a long-term persistence strategy. Rather than pursuing rapid growth of the elephant population, the initiative has stabilised their populations within human-dominated landscapes spanning reserves, corridors, and other coexistence settings. Conflict mitigation measures, such as compensation and awareness programmes, have maintained social tolerance, reinforcing the coexistence model. Over three decades, conservation priorities have shifted from poaching to habitat fragmentation and infrastructure-related mortality, reflecting evolving threats. Thus, PE exemplifies adaptive governance, where institutional coordination, policy innovation, and technological monitoring collectively sustain species persistence. This model offers particular relevance for large mammals in high human-density regions, where protected-area-centric approaches alone remain insufficient.

Initiatives & way forward

India is taking an integrated, multidimensional approach to augmenting elephant conservation through habitat management, conflict mitigation, modern technology, infrastructure planning, and improved captive elephant management. These initiatives, through enhanced monitoring, aim to enable coexistence, thus ensuring the long-term sustainability of elephant populations in diverse landscapes.

Habitat Management

Several initiatives have been launched to address habitat fragmentation and ensure secure movement for elephants. A project on the 'Integrated Conservation and Management Strategies for Ripu-Chirang Elephant Reserve' focuses on a multifaceted approach to protect critical habitat at the landscape level. The framework for the preparation of the Elephant Conservation Plan (ECP) has been introduced to provide a structured, science-driven approach to elephant management. This framework integrates ecological, socio-economic, and scientific principles to create sustainable landscapes while minimising human-wildlife conflict. Designed for adaptability, the ECP evolves with new research and environmental changes. A pilot ECP is currently being implemented in the Nilgiri Elephant Reserve to refine and optimise this strategy. Moving forward, to strengthen landscape-level conservation and improve elephant reserve management, the Management Effectiveness Evaluation of Elephant Reserves (MEE-ER) framework has been expanded to all Elephant Reserves across India with the funding support of CAMPA, ensuring a holistic and standardised approach to conservation management. Additionally, the MEE-ER is being implemented to assess and improve the management of ERs. A pilot MEE-ER study was conducted in four ERs across India: Shivalik ER (northwest), Kaziranga-Karbi Anglong ER (northeast), Mayurbhanj ER (east-central), and Nilgiri ER (south).

Retrofitting and mitigation measures

Collisions between trains and elephants represent a significant cause of unnatural elephant mortality in India. In response to the adverse effects of railway operations on wildlife, particularly the incidence of elephant-train collisions, MoEFCC and the Ministry of Railways have initiated a collaborative programme aimed at mitigating fatalities and minimising habitat disruption. As part of this initiative, comprehensive joint surveys were carried out with Indian Railways, SFDs, the WII, and PE to identify site-specific challenges. These assessments informed the development of appropriate mitigation strategies.

Following an exhaustive survey covering 127 railway stretches (110 within elephant habitats and 17 in two tiger range states) totalling 3,452.4 km, 77 stretches extending over 1,965.2 km across 14 states were prioritised for mitigation measures based on the frequency of use by elephants, tigers, and other wildlife. The recommended interventions for these 77 stretches comprise 503 ramps and grade animal passage, levelled upto the top of the sleeper, 72 bridge extensions or modifications, 39 fencing, barricading, or trenching structures, 4 exit ramps, 65 new underpasses, and 22 overpasses, resulting in a total of 705 proposed structures. Implementation details and progress are systematically tracked through the dedicated [Elephant Railway Portal](https://doi.org/10.63033/JWLS.MEHA6377), an online monitoring dashboard for this initiative. To ensure effective implementation, a dedicated portal has been launched to monitor the progress of mitigation measures across sensitive zones, helping to minimise wildlife mortalities and reduce the barrier effect of railway tracks passing through critical habitats (PE-MoEFCC-WII 2025).

Following the recommendations made by a committee constituted by the MoEFCC in 2023, various mitigation structures have been proposed to reduce collisions. In line with these recommendations, Southern Railway constructed an elephant underpass (Figure 6) on the Ettimadai-Walayar section in Tamil

Nadu, which is now actively used by elephants. More such structures are needed in the future to enhance wildlife safety. Similarly, two underpasses and an animal passage structure have been proposed for the Bongaigaon-Goalpara-Kamakhya railway track doubling project in Assam, where North East Frontier (NF) Railways will implement the project.

In addition to railway mitigation, infrastructure developments aimed at defragmenting habitats have also been undertaken by NHA. A 12-km elevated roadway has been constructed along the boundary of Rajaji National Park, featuring Asia's longest wildlife corridor to facilitate safe animal passage over NH-307 with state of art wildlife friendly lighting system (Habib *et al.*, 2024) (Figure 7). Additionally, a defragmentation study is being conducted on the Ganeshpur-Dehradun stretch of NH-307 in Uttarakhand to assess the feasibility of an elevated road for uninterrupted elephant movement. These efforts mark a significant step toward balancing infrastructure development with wildlife conservation, ensuring safer movement for elephants and other animals while minimising human-wildlife conflict (Habib *et al.*, 2026).

Human-Elephant Conflict

Given elephants' long range interstate movement, PE has proposed a Regional Action Plan (RAP) to enhance conservation and mitigate HEC. This strategic initiative focuses on habitat conservation, elephant corridor protection, and community participation, using a region-specific approach. Regional Coordination Meetings have been conducted in the East-Central, Southern, and North-Eastern regions, fostering interstate cooperation. In the Southern region, a drafting sub-committee has been formed and is actively working to formulate a structured RAP. Furthermore, a study on Understanding elephant conflict issues and suggesting conflict reduction measures (Phase II) is underway in Odisha, West Bengal, Tamil Nadu, Kerala, and Karnataka to develop effective strategies to minimise human-elephant conflict. The objective is to develop effective strategies to mitigate HEC by identifying conflict hotspots and analysing seasonal trends in incidents. The insights gained from this study will aid in formulating well-informed planning and management strategies to address the issue more effectively in the affected regions. Special emphasis is being placed on reducing human-elephant conflict caused by electrocution, with improved safety measures and awareness campaigns. Additionally, efforts are underway to establish an efficient and effective compensation mechanism, with states like Karnataka and Odisha utilising apps and IT tools to streamline compensation tracking and disbursement.

Integration of Advanced Technology for Conservation

India is integrating cutting-edge technology to strengthen its elephant conservation efforts. Advanced tracking systems, AI-driven monitoring, and drone surveillance are being deployed to mitigate human-elephant conflict and enhance real-time conservation efforts. One such effort is the development of an Intelligent Seismic Sensing Node (eleSeisAlert), which is a customisable, intelligent system designed to interface with seismic sensors to detect and classify ground vibrations caused by animal or human movement. This system is particularly valuable for wildlife monitoring, including the prevention of elephant-train collisions and perimeter surveillance. Piloted and validated over a ~400m range at Kansrao, Rajaji Tiger Reserve, Uttarakhand, eleSeisAlert provides early geo-tagged alerts to railway staff and forest guards, enabling them to slow down approaching trains and mitigate accidents. Beyond wildlife conservation, this technology helps reduce biodiversity loss and financial losses for Indian Railways. A spin-off version is also being explored as an early warning system to prevent crop-raiding by wild animals, offering a sustainable solution for human-wildlife conflict mitigation.

One novel approach adopted is the development of an AI-enabled Intrusion Detection System (IDS) that uses Distributed Acoustic Sensors (DAS) to identify the presence of elephants on railway tracks. The system components comprise optical fibres, hardware, and pre-installed elephant movement signatures. The technology warns loco pilots, station masters, and the Control Room when elephants move near the track, allowing them to take preventive measures in a timely manner. Future technological interventions should focus on stabilising and institutionalising these systems, ensuring that they are not mere stop-gap arrangements or experimental endeavours, but robust, scalable solutions integrated into national conservation strategies.

Developing a National Elephant Population Monitoring Protocol

Reliable monitoring of elephant populations is fundamental to conservation planning, management, and policy formulation. However, for long-lived species such as elephants, conservation assessments cannot rely solely on population size. Demographic parameters, including age and sex structure, survival, recruitment, reproductive rates, and population trends, are equally important indicators of population viability and long-term persistence. Consequently, a robust national monitoring protocol must move beyond simple abundance estimates to incorporate demographic and ecological metrics that provide a more comprehensive assessment of population status.



Figure 6. Railway underpass constructed to facilitate safe elephant movement along the Ettimadai-Walayar railway section in Tamil Nadu (Photo credit: Tamil Nadu Forest Department).



Figure 7. Wildlife underpass on NH-307, Delhi-Dehradun Expressway, one of the world's largest wildlife viaduct/underpass. The structure is regularly used by elephants and at least 18 other wildlife species, demonstrating its effectiveness in maintaining habitat connectivity and facilitating safe movement for animals.

India recently completed its first nationwide DNA-based elephant population assessment under the Synchronised Assessment of India's Elephant Population (SAIEE-2021), using genetic mark-recapture techniques to generate a scientifically robust estimate of wild elephant abundance (Qureshi *et al.*, 2025). This represents a major methodological advance and establishes a new baseline for future monitoring. However, because of the shift to a fundamentally different estimation approach, these results are not directly comparable with previous population estimates and should be viewed as the starting point for a new generation of science-based elephant monitoring.

Recognizing the need for a standardized national framework, Project Elephant and the Wildlife Institute of India have undertaken extensive evaluations of alternative monitoring approaches. Comparative studies in the Western Rajaji Tiger Reserve assessed multiple direct and indirect methods, including line transects, dung counts, camera-trap-based models, and genetic mark-recapture, evaluating their precision, bias, operational feasibility, and cost-effectiveness (Habib *et al.*, 2025). These studies provide the scientific basis for selecting appropriate methods for different landscapes and management objectives.

Ongoing research by Project Elephant and the Wildlife Institute of India is further evaluating the efficacy, scalability, and robustness of alternative methodologies to refine a nationally standardized monitoring protocol that balances scientific rigor, operational feasibility, and long-term conservation needs (Habib *et al.*, 2025).

Management and Welfare of Captive Elephants

PE is actively working to improve the welfare of captive elephants by developing essential guidelines and best practices. These initiatives include the publication of Guidelines for Foot Care of Captive Elephants, a document on 'Best Practices in Captive Elephant Management for Elephant Handlers', a comprehensive guide on 'Principles of Captive Elephant Management', and the 'Advisory on tusk trimming'. Efforts are also underway to complete DNA profiling of captive elephants, which will aid in their better management and protection. Recognising the need for capacity building, there has been consistent demand from states like Assam to establish a Mahout Training Institute. Proposals have been put forth for institutes like the Salim Ali Centre for Ornithology (SACON), Coimbatore, to set up mahout training schools, considering the poor health and husbandry conditions of captive elephants. Rescue and rehabilitation centres are also being planned to care for elephants with chronic ailments.

India's way forward in elephant conservation focuses on several crucial aspects, including policy advancements, technological innovations, regional cooperation, and grassroots engagement. The completion of DNA profiling of captive elephants will further bolster the management strategies. Efforts to reduce HEC, particularly electrocution incidents, will continue with stronger safety measures. Establishing efficient compensation mechanisms, such as those implemented in Karnataka and Odisha, will ensure timely support for affected communities. The efficacy of physical barriers in conflict-prone zones will be assessed, with recommendations for state forest departments. Capacity building for mahouts, handlers, and caretakers will be expanded with dedicated training institutions in regions

such as Assam and Bandhavgarh. Conservation management of elephant corridors, such as those in Segur (Tamil Nadu) and Odisha, should be prioritised. Additionally, technological interventions to monitor elephant movements and prevent train collisions will be stabilised and institutionalised. Finally, better mitigation measures and retrofitting of linear infrastructure, such as the Ganeshpur-Dehradun road and Deepor Beel elevated corridor, will facilitate safer elephant movement and minimise conflicts.

The interventions indicate that PE has effectively mitigated population decline by adopting landscape-level coexistence management, emphasising ecological connectivity and conflict mitigation, rather than relying solely on traditional recovery-oriented protection. India's comprehensive conservation strategy, integrating policy advancements, technological innovations, regional cooperation, and grassroots engagement, provides a strong foundation for the long-term survival of elephants. PE, as the nation's flagship initiative, reinforces this framework through science-based management and coordinated action. Sustained efforts, adaptive management, and cross-border collaboration will be crucial to ensuring that elephants continue to thrive across India's diverse landscapes, in line with the country's forward-looking vision to emerge as a global model in elephant conservation.

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CONFLICT OF INTEREST

Bilal Habib & Parag Nigam hold editorial positions at the Journal of Wildlife Science. However, none of them participated in the peer review process of this article except as authors. The authors declare no other conflict of interest. The authors declare that they have no competing interests.

DATA AVAILABILITY

Data is available from the corresponding author on request.

AUTHOR CONTRIBUTIONS

R.K.P., A.N., P.N., and B.H. conceived the study. R.K.P. led the compilation of information, literature synthesis, data analysis, and preparation of the first draft. S.P.Y., G.S.B., D.M., A.M.G., G.S., and A.N. contributed to data compilation, interpretation, and manuscript review. P.N. and B.H. provided technical guidance, conceptual inputs, and critical revisions throughout manuscript development. R.K.P., A.N. and B.H. coordinated the overall preparation of the manuscript. All authors reviewed, edited, and approved the final version of the manuscript.

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Gaja-sastra: India's forgotten Elephant Science

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Abstract

This article revisits *Gaja-sastra*, the forgotten Indian science of elephants, and traces the evolution of elephantology in India from the 3rd century BC onwards. Drawing on classical texts such as *Gajasastra*, *Hastayurveda*, *Matanglila*, *Manasollasa* and *Hastividya*, it shows how ancient Indian scholars developed systematic knowledge of elephant behaviour, medicine, training, cognition, and welfare through observation and practical experience. Far from being purely mythological, these traditions embodied a proto-scientific framework that integrated ethics, management, and ecological understanding. At a time of intensifying human–elephant conflict and wider conservation challenges, revisiting these indigenous knowledge systems offers valuable insights into coexistence, animal welfare, behavioural understanding and culturally rooted approaches to elephant management that may inform current conservation practices.

Keywords: Ancient Indian science, Asian elephant, elephant medicine, ethology, traditional ecological knowledge.

Introduction

In the present day, elephants are too often seen as antagonists, especially when incidents of human–elephant conflict receive wide media attention because they involve loss of life or property. In such discussions, however, we often forget the depth of the human–elephant relationship. Archaeological evidence suggest that hominin engagement with elephants extends deep into pre-history (Agam & Barkai, 2018; Ben-Dor *et al.*, 2011). Asian elephants are thought to have emerged in what is now Myanmar and to have spread across Asia, while several hominin species already inhabited the region (Lim & Campos-Arceiz, 2022). Although the phrase “evolutionary times” should be used cautiously, humans and elephants do share a very long history of co-existence and interaction. Particularly in India, elephants were integral to society from at least the Indus Valley period and were referred to as ‘*Pilu*’, an Indic word derived from tooth or tusk (Ketkar, 1952). Subsequently, names such as *Ibha*, *Hastin*, *Gaja*, *Kunjara* and *Matang* (Witzel, 1997) appeared in Sanskrit and other ancient and medieval texts (Ketkar, 1952). Many of these names seem to derive not only from elephants’ association with humans, but also from close attention to their ecological roles, physical traits, and behavioural characteristics. In Nilkantha’s *Matanglila*, for instance, elephants are called *Karin* because of the long trunk, and *Danti* or *Dvirada* because of the tusks. The name *Ibha* points to a behavioural disposition, probably reactivity or fearfulness, while *Abhyadhika* suggests majestic form. Names such as *Naga*, *Kunjara*, *Padmi*, and *Gajah* also appear to arise from ecological and behavioural observations, where *Kunjara* refers to one whose feet crush the earth, *Naga* suggests mobility across varied terrains, *Padmi* refers to fondness for lotuses, and *Gajah* is one who roars or conquers. At the same time, some names clearly reflect the elephant’s role in human society, warfare and statecraft. *Ashtaprahara*, for example, refers to one who strikes with eight blows, one each with trunk, tail, two tusks and four feet. As documented in *Matanglila*, these synonyms themselves reflect the depth and systematic nature of ancient Indian knowledge on elephant biology, behaviour and ecology (Edgerton, 1985; Dhammaloka, 2025).

The story of elephants did not only remain confined to religious or *Puranic* literature and story traditions in India. Over time, it also took shape into a rich body of manuals and scholarly works that went beyond mythological and symbolic representations and were grounded in close observations and practical engagement (Witzel, 1997). Since the rise of the ancient kingdoms, elephants occupied a central place in polity, diplomacy and warfare (Bilhana & Bharadwaj, 1958). They became associated with strength and auspicious power. As a result, Indian society developed a systematic and unparalleled knowledge tradition on elephants long before modern science assumed its present form.

The ancient systematic study of elephants, also referred to as *Gajasutra* or Indian elephantology (Krishnaswamy, 1952; Geetha, 2013), has roots in early historic India. Over time, this knowledge system assumed a more structured form through works such as the *Gaja-sastra* and the *Hastayurveda*, traditionally attributed to Palakapya Muni (Cheeran, 2013). Although the exact dates of these writings remain uncertain, they are frequently credited to sage Palakapya, who is often placed between early historic and early classical periods of Indian history. Over time, these texts also appear to have undergone transmission, compilation, and redaction (Cheeran, 2013; Pollock, 2006; Trautmann, 2019). Even so, these writings marked a major turning point by transforming accumulated practical knowledge into an organised system of understanding. For more than two millennia thereafter, scholars, physicians, trainers, and elephant handlers enriched this specialised body of knowledge devoted entirely to elephants. This tradition was not simply mythological or religious (Pollock, 2006); it included technical manuals related to classification, veterinary medicine, behaviour, training, and long-term management of elephants in captivity. It is therefore useful to think of it as a proto-scientific tradition in elephant knowledge. In the context of contemporary human-elephant conflict, debates on captivity are confined to perception rather than looking into the annals of elephant knowledge systems and practices of co-existence since time immemorial (Rangarajan, 2012), and the future of conservation is going to be challenging with growing economic aspirations, revisiting this forgotten science and practice on elephants in the country is going to be crucial and more than just an academic exercise to make youth aware of our history with elephants and kind of traditional knowledge system the country had, as well as the long history of how Indian society understood, used and lived with elephants.

This review draws upon both primary and secondary sources. Primary sources include available editions and translations of classical elephantological treatises such as *Gaja-sastra* and *Hastayurveda*, Nilkantha's *Matanglila*, Somesvara III's *Manasollasa* and *Hastividya*. These texts are read alongside contemporary historical and academic evaluations. Secondary literature was used to compare scholarly interpretations and provide historical context.

Gaja-van, Gajadhyaksha and a symbol of royal fortune in ancient times

If we look closely at history, elephants were never peripheral animals in Indian society but have always demanded deep knowledge and sustained care since the earliest times. They stood at the centre of warfare, statecraft, forestry, transport and kingship (Chitrav, 1937; Bilhana, & Bharadwaj, 1958). During that time, trained elephants could determine the outcome of a battle, haul enormous timber (Watt, 1890) or symbolise royal authority. Raising them was a long-term commitment, and maintaining them required constant care and vigilance. Losing them to illness, stress, or mishandling was an enormous political and economic setback. Managing such animals, enormous in size, endowed with great physical strength, sharp intelligence and emotional complexity, through casual treatments and ritualistic practices alone was impossible, and hence it demanded a serious, systematic and experience-based approach, which ultimately gave rise to rich traditions of elephant knowledge in India. Elephants, by their very nature, compelled humans to observe closely, predict their behaviour, test methods and pass on reliable knowledge to generations. They demanded systems that worked not once, but repeatedly. In short, elephants forced commitment and disciplined engagement from people in matters of their upkeep, health and care. This is how elephantology in India emerged and evolved, and interestingly, not as an abstract theory, but as applied knowledge shaped by necessity, observations made and traditional acquired wisdom of the community.

Long before the emergence of specialised treatises on elephants, the *Arthashastra*, written in the 3rd century BC by Kautilya, treated the 'Gaja' as a vital pillar of state power, combining military, economic, and administrative significance. The Gaja formed an essential component of the army (Chitrav, 1937), as they had the ability to break enemy formations, breach fortifications, and generate immense psychological shock in warfare (Trautman, 2019). Recognising their strategic importance, the *Arthashastra* prescribes a highly organised system for their management under a designated superintendent called *Gajadhyaksha*, who oversaw capture, training, feeding, and healthcare. The text also emphasises the protection of elephant forests; the *Gaja-van*, reflecting an early form of state-controlled conservation, where the unauthorised killing or injury of elephants was strictly prohibited and punished. Detailed classifications are provided based on region, physical attributes, and temperament, indicating a proto-scientific approach to selection and training. Elephants were considered royal assets, often used in diplomacy and as symbols of sovereignty, enhancing the prestige of the king (Blochman, 1927). Overall, the *Arthashastra* presents elephants not merely as animals but as carefully regulated instruments of governance and warfare, illustrating an advanced understanding of wildlife management, military logistics, and statecraft in ancient India (Shamashastry, 1961; Vachaspati, 1962).

In addition to the *Arthashastra*, the 'Brihat Samhita' of Varahamihira contains several references to elephants, though not in the form of a full-fledged elephant manual like the *Gaja-sastra* texts (Bhat, 1981; Sastri & Bhat, 1947). Instead, elephants appear within a broader framework of omens, physiognomy, royal symbolism, and natural science. In the text, elephants are discussed mainly in terms of auspicious and inauspicious characteristics called *lakshana*, as described in Chapter 67, *Hasti-laksana* (Bhat, 1981). This chapter classifies elephants into four morphological types- *Bhadra* (prosperous), *Manda* (slow), *Mrga* (wild) and *Sankirna* (hybrid), depending on body proportion, tusk shape, skin texture, gait, colour and temperamental disposition. Elephants with ideal physical traits such as honey coloured tusks, symmetrical limbs, large frontal lobes and vigorous musth discharge were considered auspicious and suitable for royal use. Those who seemed otherwise were deemed unsuitable. Varahamihira describes ideal traits of elephants suitable for kings, such as the right proportion of limbs, smooth skin, deep and resonant sounds, and a calm yet powerful temperament. Such elephants were believed to bring victory, prosperity, and stability to the kingdom. Deformities or unusual features were treated as inauspicious signs, potentially indicating misfortune. While rooted in cosmological beliefs of the period, these classifications were based on detailed morphological observations that parallel systems of *Gajasutra* and *Matanglila* also describe. Conversely, Chapter 94, *Hasti-vestita*, of *Brihat Samhita* shifts more clearly toward behavioural description, listing elephant behaviour and their perceived meanings (Bhat, 1981). There are two distinct components in the chapter that need to be discussed separately. First, the text accurately documents a number of behavioural indicators that are recognisable to contemporary ethology and veterinary science on an empirical level, like musth, vigorous movements and patterns of vocalisation are described as signs of vitality, while reduced appetite, abnormal gait, absence of ear movement, excessive urination, weeping eyes and restlessness are signs of distress. Second component interprets these behaviours using cosmological – omenological framework that is characteristic of this historical period, but must be acknowledged as such, like breaking of tusk is interpreted as royal misfortune and the outcome with an elephant-crocodile encounter is presented as predictive of royal fortune. These interpretations belong to systems of divination and cosmological beliefs (*Nimitta-sastra*) that dominated ancient Indian statecraft. In other words, the *Brihat Samhita* is best understood as an encyclopaedic text that contains observational content with a broader astrological and omenological framework. The observational theory merits acknowledgement as a contribution to scientific natural history and should be read as such (Bhat, 1981; Sastri & Bhat, 1947).

A discipline of science and traditional knowledge

One of the clearest signs that elephantology was a serious intellectual tradition is its disciplinary structure. Elephant knowledge in India was not merely scattered folklore but organised documentation with distinct domains, each addressing a specific problem. The five major scriptures that form the basis of Indian elephantology are *Gajasastra*, *Hastyayurveda*, *Matangalila*, *Manasollasa*, and *Hastividya*. The ancient works of *Gajasastra* and *Hastyayurveda* are traditionally attributed to Palakapya Muni. Although the exact dates remain uncertain, scholars regard them as the earliest surviving treatises devoted to elephants and their management (Cheeran, 2013; Trautmann, 2019). The *Gajasastra* focuses on the classification, capture, and training of elephants, whereas the *Hastyayurveda* deals exclusively with elephant medicine and treatment for diseases. A medieval work, *Matangalila* by Nilakantha, written around the 12th century AD, examines the behaviour and temperament of elephants and focuses on their ethological sensitivity and emotional states (Dhammaloka, 2025). During the same period, the Chalukya king Somesvara III wrote a text called *Manasollasa*, also known as *Abhilashitartha Chintamani*, written in Sanskrit and dealing with royal life, administration, arts, and science. One of the important texts of the scripture is devoted to elephants, reflecting the crucial role played by elephants in medieval Indian polity and warfare (Sadhale & Nene, 2004a). A modern but regional text, written by Sukumar Barkaith in Assamese around the 18th century AD, namely *Hastividya*, adds value to Indian elephantology by applying knowledge described with illustrations.

(i) *Gajasastra: The elephantology*

Traditionally attributed to Palakapya Muni, *Gajasastra*, one of the earliest known treatises devoted to elephants, is in many ways a field manual. It describes elephants in careful detail, including body proportions, posture, skin texture, tusk shape, eye movement, gait and vocalisation. These physical traits were not catalogued for aesthetic interest. They were used to predict temperament, learning ability and behaviour under stress. Many body features were associated with calmness and reliability, while others were linked to volatility or resistance to training. Trainers were warned which elephants required patience and which were best avoided altogether. Like many premodern technical works, *Gajasastra* is a blend of cosmological and mythical frameworks with practical facts. In addition to providing comprehensive explanations of elephant morphology and behaviour and management, the literature also includes a classification of elephants, which is based on more general Indian religious and cultural traditions. It is more appropriate to consider this book as a product of an intellectual framework where metaphorical perspectives and practical knowledge co-exist. The text's observational and experience-based aspects have contributed to the advancement of elephant management, behavioural understanding and veterinary practice. The logic is familiar to anyone who studies animal behaviour today, viz., observe consistently, identify correlations, and adjust practice accordingly.

(ii) *Hastyayurveda: Health and medicinal system of elephants*

During the same period, circa 5-6th century BC, the Palakapya Muni composed another important classical text, *Hastyayurveda*, on the subject of elephant health and the medicinal system for elephants, while describing the elephant's behaviour and ethological aspects. The scripture is among the world's earliest veterinary traditions and is devoted entirely to elephant health. It describes elephant anatomy in detail, classifies diseases by observable symptoms, and prescribes treatments derived from plants, minerals, and carefully regulated diets.

In this text, the illness is not attributed to divine punishment or malevolent spirits, but is diagnosed through signs such as appetite loss, changes in gait, discharge, swelling, or behavioural

shifts. Preventive care receives as much attention as treatment in the scripture, and cleanliness, exercise, diet, seasonal adjustment, and rest are emphasised repeatedly as part of the health management system. In effect, elephants were treated as patients, and the medical theory reflects premodern ideas about the body, while the methods adopted for treatment were empirical. Further, treatments are evaluated by whether they work or not, and therefore, the knowledge persists because of its effectiveness and not because it is a sacred scripture.

(iii) *Matangalia: Understanding elephant minds*

By the medieval period in India, elephantology had expanded beyond the body to include the minds of elephants. The *Matangalila*, written by Nilakantha in the 12th century AD, devotes significant attention to the behaviour and emotional states of elephants, which is unique in many respects. It describes how elephants signal fear, stress, fatigue, illness, or impending aggression through changes in posture, movement, sound, and interaction with handlers. Some of these signs are framed as omens, a reminder that empirical observation coexisted with premodern interpretive frameworks. But many function as practical warnings. An elephant behaving in a particular way is not foretelling fate but signalling distress, and modern ethology also rests on the same insight that behaviour is information. The emphasis on long-term temperament is especially notable. It is important to understand that elephants are essentially wild animals and their welfare is closely linked to their natural, social and ecological environments. In the dialogue between Palakapya Muni and King Romapada, elephants are depicted as suffering when taken away from their natural habitat and deprived of their natural freedom. The narrative suggests that captivity and separation from natural conditions can produce distress and disease. This observation, despite being expressed within the cultural and philosophical language of its time, resonates with modern understandings of animal welfare, which acknowledge limitations on natural behaviour, movement, and social interaction as major stressors in captive elephants (Sukumar, 2011; Locke & Buckingham, 2016). These texts recognise that trauma has consequences, which is a significant knowledge for handling elephants in captivity.

In *Matanglila* (Edgerton, 1985), elephants are classified based on their behavioural traits, such as *Deva* (god/king), *Danava* (antigods), *Gandharva* (celestial spirit), *Yaksha* (demigod), *Rakshasa* (demons), *Manava* (humans), *Pishacha* (malevolent spirit) and *Uraga* (serpent), according to the qualities they possess. Another classification, based on physical features, dividing elephants into four categories - *Bhadra* (prosperous), *Manda* (slow), *Mrga* (wild), and *Sankirna* (hybrid), which is similar to *Brihat Samhita*, is also mentioned here. Here, *Bhadra* and *Manda* are considered superior breeds, while *Mrga* is inferior. *Sankirna* is a mixture of both superior and inferior breeds. Similarly, elephants are also classified based on their sensitivity into seven groups, such as *Atyarthvedi* (over-sensitive), *Uttanvedi* (expressive), *Gambhirvedi* (less reactive), *Mandavedi* (slow to respond), *Mriduvedi* (gentle), *Tikshnavedi* (highly alert and perceptive) and *Chanchalvedi* (restless). In addition to these classifications, elephants were also identified based on their three fundamental regulatory principles that govern physiology, health and disease, or *Tridosha* (*Vata*, *Kapha* and *Pitta*), as per Ayurveda (Zimmerman, 1988), for their treatments (Wujastyk, 2003). *Vata* or wind (air principle) drives movement and kinetic force; *Pitta* or bile (fire principle) drives metabolic energy; and *Kapha* or phlegm (water/earth principle) drives structural energy and cohesive force. Regarding elephant health science, the *Bhadras* were considered to have all the principles balanced in them, and hence these elephants were healthy. It was considered that phlegm (*Kapha*) is high in *Manda*, therefore, they were slow and dull. Elephants with high bile (*Pitta*) in *Mrga* made them angry and agile easily. Such knowledge helped in treating and caring for elephants in a scientific way during those days.

There is a specific verse in Nilkantha's *Matanglila*, particularly from the conservation perspective, which states a prohibition against the capture of a pregnant she-elephant (*Garbhini*) or accompanied by a calf (*Dhenuka*) (Edgerton, 1985; Geetha, 2013). The text suggests that capture of such elephants can bring ruin to the royal treasury, and that such elephants, if captured, should be released in a sacred grove or forest or a temple. This statement expresses a practical prohibition of the capture of pregnant females and calves from the population and a theological backing to justify it. Given that the gestation period of elephants is 20-22 months and the inter-birth interval is about 4-5 years (de Silva, 2013), removal of pregnant or lactating females will carry a large demographic cost. Capture of lactating females will also cause the death of dependent calves. This provision in *Matanglila* is directly related to modern elephant population biology. This clause implies that ancient Indian elephantological methods adopted ecological protection measures within their standard and practical frameworks, even when the stated justifications were religious or omenological in nature, when read alongside *Kautilya's* broader framework of elephant forest reserves and wildlife protection in Arthshastra (Tisdell, 2005).

(iv) *Manasollasa: Importance of Gaja in Indian polity and warfare*

During the period of Western Chalukya king Somesvara III in the 12th century AD, another encyclopaedic work was written in Sanskrit, which is known as *Manasollasa* or the 'Delight of mind'. It is also known as *Abhilashitartha Chintamani* (Wish-fulfilling Gem). The text is not solely focused on elephants. However, one of the important sections of the text is completely and elaborately devoted to *Gaja*, which is an example of the critical role played by the elephants during the medieval Indian polity and warfare (Shamashastry, 1926).

Referring to the edition of *Manasollasa* (Shrigaonkar, 1925; Shrigaonkar, 1961), the elephant section discusses the classification of elephants based on their physical features, temperament, and regional origin. Elephants are categorised according to auspicious and inauspicious marks or *laksanas*, helping kings select suitable animals for war, ceremonial processions, and royal service. The text also describes methods of capturing, taming, and training elephants, emphasising patience, proper diet, and humane handling. Detailed attention is given to the care and management of elephants, including feeding practices, daily routines, and stable maintenance. Another significant aspect is elephant diseases and their treatment, where traditional veterinary knowledge is presented using herbs, oils, and rituals.

Perhaps the most striking feature of *Manasollasa* is its insistence on compassion. It encourages keeping elephants free from stress, otherwise their power and capabilities become counterproductive and render them unstable. The scripture highlights that elephants are intelligent animals and that maintaining their mental health is equally important. It underlines that calm handling, patience and respect are prerequisites for effective training and the long-term reliability of elephants. Compassion is not presented as moral ornamentation. It is framed as a technique.

However, an honest evaluation of *Manasollasa's* treatment of elephants must also take into account a section that directly contradicts its compassion-centred husbandry principles. Section IV of Chapter 3 of the main text is *Gajavahyali* or sports with elephants in the arena consists of 256 verses dedicated entirely to preparing elephants for arena sports and combat as royal entertainment (Sadhale & Nene, 2004b). This section prescribes detailed pharmacological protocols for inducing musth before arena events. This is deeply problematic from a modern animal welfare perspective as musth is a physiologically and psychologically extreme state and altering it in captive elephants through pharmaceutical manipulations can cause extreme stress in animals with no capacity to respond through

behaviour that naturally resolves it (Doyle *et al.*, 2024). Thus, *Manasollasa* reflects the structural ambiguity of the human-elephant relationship in ancient India. A document concerning animal welfare and conservation must acknowledge both aspects without favouring one over another. The compassion discussion in *Manasollasa's* husbandry sections is real and historically significant, and so is the harm prescribed in *Gajavahyali* chapter of it. In order to understand appropriately what ancient Indian elephantology can or cannot provide to modern conservation and welfare frameworks, it is more suitable in scientific discourse to deal truthfully with this dilemma rather than selectively highlighting the former.

The treatise also highlights the strategic importance of war elephants, noting their psychological impact on enemy forces and their role in breaking military formations.

The elephant section of the text, in general, serves as a valuable historical source for understanding ancient Indian animal science, military organisation, and royal culture, demonstrating the high status and symbolic power of elephants in medieval India.

(v) *Hastividya: Pictorial pedagogy with regional knowledge*

By the early modern period, elephantology had become increasingly applied and region-specific. The *Hastividya* (Ocean of Elephant Knowledge), another scripture on elephant science, was composed in 1734 CE under the patronage of the Ahom Kings of Assam. This pictorial guide, composed in the Brahmaputra Valley, was written by Sukumar Barkaithe and elaborated on elephant care, diseases, and training, incorporating regional knowledge and practices of Assam during the Ahom kingdom.

Interestingly, the illustrations in the *Hastividya* are not decorative but serve a pedagogical function, making knowledge easier to transmit and standardise. This also supports the reproducibility of knowledge and makes it accessible to those who are not even literate, a hallmark of mature scientific traditions. Another notable aspect of the treatise is that it integrates classical knowledge from *Gajasastra* and *Hastyaurveda* with local ecological practices, including forest-based capture techniques, riverine management, and region-specific medicinal plants. Detailed illustrations depict elephant anatomy, diseases, surgical instruments, harnesses, and stable layouts, making the text uniquely valuable for historians of science. The scripture also recognises that elephants, forests, and climates differ across regions and therefore requires differential treatment based on local resources and traditions. No one-size-fits-all methods of elephant capture, care, and coexistence apply. Its descriptions of elephant habitat, capture techniques, and seasonal movement reflect thorough knowledge of floodplain dynamics, marshy grasslands, and shifting river channels of the Brahmaputra river, though the Brahmaputra is not named explicitly.

The training section of the scripture emphasises non-violent methods and long-term bonding between mahout and elephant. The texts also reflect early conservationist sensibilities, warning against over-capture and neglect of breeding populations. Its production within a living elephant management culture makes it an invaluable ethno-scientific document.

These five important scriptures are a testament to the level of specialisation in Indian culture regarding elephants in the past. No other animal, except elephants in India, in the premodern world generated such a sustained, technical and varied literature across the centuries. Nowhere in the world did such a knowledge system on elephants exist as it did in the Indian subcontinent.

Neither truly a modern science, nor a mere myth

Recognising *Gaja-sastra* as a proto-scientific document does not mean claiming that ancient India practised modern science in any straightforward sense. These traditions existed alongside cosmology, astrology and customary beliefs and practices. Elephants were often deeply entangled with kingdoms, political power and stability (Trautmann, 2019). Yet modern science itself emerged from similar mixtures of observation, belief and correction over time. In India, elephantology, through its various texts, shows disciplined observation, functional verification, cumulative knowledge and ethical reflections. These are not incidental features but the foundations of scientific thinking.

Why this matters today

Elephants are once again at the centre of public debate. Human-elephant conflict is intensifying across India and in Asian elephant range states (Roy *et al.*, 2025). Captive elephants remain the focus of ongoing concern about care, husbandry and welfare (Brown *et al.*, 2020). Habitat fragmentation and climate stress continue to threaten wild populations as land use changes rapidly across elephant landscapes (de Silva *et al.*, 2023). Conservation science now places increasing emphasis on behavioural understanding, stress reduction, long-term care and ethical coexistence (Van de Wat *et al.*, 2024), precisely the principles that elephantology articulated centuries ago. These ideas are not borrowed but are based on deep-rooted Indian knowledge systems and natural history. Recognising this does not mean romanticising the past or rejecting modern science. It means understanding that scientific rationality has many histories and that care for the living world has always been central to serious knowledge. India did not merely worship elephants; they were well studied and taken care of, even for their mental well-being. At a moment when we are struggling to live alongside these giants without destroying them, recalling the forgotten science may be no less relevant than ever.

The elephantological literature also contains ethical insights that remain relevant today, particularly the recognition that elephants are sentient beings whose welfare is closely linked to freedom of movement, social bonds and their environment. Palakapya's observation that elephants experience distress when removed from their habitat anticipates current concerns about captivity, behavioural stress and consequences of restricting natural behaviour. This perspective offers a useful historical foundation for present discussions on elephant management, rehabilitation and welfare-oriented conservation.

One of the most important lessons from ancient Indian elephantology is the need to take elephant behaviour and cognition seriously (Mumby & Plotnik, 2018). Elephants are highly intelligent and social animals (Daniel, 1998; Sukumar, 2011), and they therefore require care and sensitivity when handled (Bates *et al.*, 2025; Veasey *et al.*, 2006). At the same time, these classic texts should not be read uncritically through a modern conservation lens. Most of these texts were produced in royal and administrative contexts, and elephants were valued as assets for warfare, transport, ceremonial functions and statecraft. Much of the knowledge they contain was therefore developed to support training, capture, maintenance and effective use of elephants in captivity. Their objectives fundamentally differ from the modern idea of wildlife conservation, which prioritises the persistence of free-ranging populations. Nevertheless, these texts also contain detailed observations on elephant behaviour, stress, health, social relationships and their environmental requirement. While the historical text must be acknowledged, the noted observations provide valuable insights into human-elephant engagement, and these may contribute to present discussions on elephant welfare, captive management and human-elephant interactions.

Studies indicate that the intensity of human-elephant conflict varies not only because of anthropogenic actions, including mitigation measures, but also because of moves taken by elephant herds to avoid or confront situations (Guarnieri *et al.*, 2024). Further, the depth of elephant studies in ancient times indicates the need to recalibrate research on elephant ethology and ecology at present, especially the aspects of dealing with the human-elephant conflict in human-dominated landscapes.

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CONFLICT OF INTEREST

The author declare no competing interests.

DATA AVAILABILITY

No additional data is used in this commentary.

AUTHOR CONTRIBUTIONS

All work was done by the single author.

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Truncated Life: Patterns and Causes of Elephant Mortality in the state of Chhattisgarh, India

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Abstract

Human-elephant conflict (HEC) in Chhattisgarh, India, has intensified over the past two decades, threatening both elephant populations and rural livelihoods. This study analysed 218 elephant mortality incidents recorded between 2000 and 2023 to identify spatial, temporal, and ecological patterns underlying these deaths. Findings indicate electrocution as the leading anthropogenic cause, particularly affecting adult males, with mortality peaking during the monsoon season. Spatial analysis identified hotspots such as Dharamjaigarh, Chhal, and Jashpur, where the highest number of electrocution cases overlapped with key elephant corridors and movement routes. Land use and land cover (LULC) analysis (2000–2024) showed a -7.26% change in forest cover and a substantial increase in cropland and built-up areas, indicating habitat fragmentation as a key driver of conflict. Generalised linear models identified proximity to croplands, elephant reserves, and edge density as significant predictors of mortality risk. Conservation measures must include monitoring distribution lines used in electric fencing, insulating power lines (selected locations), restoring habitat connectivity, and implementing AI-based monitoring tools. Additionally, community engagement through early warning systems and compensation schemes can reduce retaliation and foster coexistence. This study highlights the urgent need for integrated landscape-level planning and intersectoral coordination to mitigate HEC and secure the long-term survival of elephants in fragmented, human-dominated landscapes.

Keywords: Adult mortality, dharamjaigarh, electrocution, electric fencing, habitat fragmentation.

Introduction

Asian elephants have attracted global attention for conservation as their number has reduced by ~50% since the 1950s within a couple of elephant generations (considering about 60 to 75 years as the average lifespan of an elephant), along with rapid shrinkage of their habitat across the range countries (Sims *et al.*, 2015; de Silva *et al.*, 2023). The increase in human settlements and agricultural practices in Asia has led to widespread destruction of elephant habitats and reduced connectivity within the landscape (Jarungrattanapong & Olewiler, 2024; de Silva *et al.*, 2023; Shaffer *et al.*, 2019). Over the past decade, human-elephant conflict (HEC) has emerged as a major challenge across several Asian countries (Montez *et al.*, 2021; Shaffer *et al.*, 2019; Wilson *et al.*, 2015). These conflicts have resulted in economic costs and caused injuries and fatalities among both humans and elephants (Bhagat *et al.*, 2017; Köpke *et al.*, 2024). With human activities increasingly encroaching on elephant habitats, HEC poses a critical threat to their survival across their range (Billah *et al.*, 2021; Shameer *et al.*, 2024). Therefore, a deeper understanding of land-use dynamics and integrated management inside and outside PAs is vital for conserving elephants in HEC-prone landscapes. In Central India, elephant habitat covers about 21,000 km² across Jharkhand, Odisha, Chhattisgarh, and southern West Bengal, supporting nearly 10% of the country's elephant population (Menon *et al.*, 2017, Baskaran *et al.*, 2011). Although this landscape supports a relatively small elephant population, it records one of the highest human fatalities (Natarajan *et al.*, 2023a). Central Indian forests are severely fragmented and degraded by intensive agriculture, shifting cultivation, mining, and expanding infrastructure. Historically, elephants were distributed across southern Uttar Pradesh, Madhya Pradesh, to Chhattisgarh (Baskaran *et al.*, 2011). Chhattisgarh has a small population of elephants that initially travelled from Jharkhand and Odisha in the 1980s and 1990s. Over the past few decades, the forested areas in these two states have experienced degradation due to activities such as illicit logging,

encroachments, industrialisation, and mining (Singh, 2002). Chhattisgarh serves as a corridor with this larger regional pattern of elephant range expansion driven by habitat degradation and fragmentation in the neighbouring states such as Jharkhand, Odisha and southern West Bengal (Debata *et al.*, 2013; Singh, 2002). According to Forsyth's historical account from 1889, elephants were once present in northern Chhattisgarh and experienced local extinction throughout the early years of the 20th century (Singh, 2002). However, in recent decades, increasing anthropogenic pressure in the adjoining states has forced elephant to venture into the state of Chhattisgarh (Natarajan *et al.*, 2023b). As reported, only 18 elephants moved into Chhattisgarh in 1988, but from 1998 onwards, the population gradually increased, reaching 247 individuals by 2017 (MoEF&CC, 2017). The incidence of human-elephant conflict has been on the rise since 2000 due to the steady increase in the number of migratory elephants entering Chhattisgarh (Singh, 2002). Presently, Chhattisgarh hosts an expanding metapopulation of 451 (Qureshi *et al.*, 2021–2025). Asian elephants, occurring across fragmented forest-agriculture mosaics in the northern districts like Surguja, Korba, Raigarh, Jashpur with individual elephant utilising annual home ranges of around 3,000 km² (Natarajan *et al.*, 2023b).

The issue of human-elephant conflict presents a substantial hindrance to conservation endeavours and rural livelihoods in various regions of India, including Chhattisgarh. This conflict is marked by elephants inflicting damage to crops and property, resulting in human and elephant casualties (Natarajan *et al.*, 2025). Understanding the drivers of elephant mortality is critical for devising effective conservation and conflict-mitigation strategies, especially in regions where human-elephant interactions are intense. Chhattisgarh has emerged as one of the most challenging landscapes for elephant conservation in India, with consistently high rates of mortality recorded over the past two decades (Habib *et al.*, 2025). Despite the seriousness of the issue, a systematic evaluation of causes, spatial distribution, and demographic correlates of elephant deaths in this region remains lacking. First, investigating the temporal and spatial changes in mortality causes will help identify whether certain hazards, such as electrocution, poisoning, and other anthropogenic threats, have intensified or shifted geographically over time. This information is essential to target high-risk zones for mitigation measures. Second, analysing the association between age/demographic classes and specific mortality causes can provide insights into vulnerability patterns. For instance, calves and juveniles may be more susceptible to accidents or starvation, while adults may face higher risks from conflict-related electrocution or poisoning. Such demographic insights are vital for prioritising management interventions. Third, linking mortality data with landscape features and anthropogenic factors (e.g., habitat fragmentation, agriculture expansion, mining, power lines, or linear infrastructure) will help explain underlying drivers of mortality. This spatially explicit approach will not only clarify how human pressures shape mortality patterns but also guide landscape-level planning, such as corridor restoration, safe power infrastructure, and conflict-reduction strategies.

By addressing these three aspects, the study will provide a comprehensive, evidence-based framework to reduce elephant mortality in Chhattisgarh. The findings will be directly applicable to conservation policy, inform conflict mitigation programs, and support long-term coexistence between people and elephants in this high-conflict state.

Therefore, in the present study, we investigate the changes in elephant mortality causes and their spatial distribution in Chhattisgarh over the past two decades (2000–2023). The specific objectives are as follows: (i) How did the causes of elephant mortality and their spatial distribution in Chhattisgarh

change over the past two (2000–2023) decades? (ii) Is there any significant association between the age and demography of deceased elephants and specific causes of mortality, particularly focusing on anthropogenic stressors? (iii) How do landscape and anthropogenic features over the same periods potentially influence these mortality patterns?

Study Area

The study was conducted in Chhattisgarh, India (Figure 1), which lies between 17°46'N and 24°05'N latitude and 80°15'E and 84°20'E longitude. Chhattisgarh has a total geographical area of 135,192 km², of which 55,547 km² (41.09%) is under forest cover. It has a hot and humid tropical climate with three distinct seasons: summer (March to May), rainy (June to October), and winter (November to February). Summer temperatures range from 30 °C to 45 °C, while winter temperatures range from 8 °C to 25 °C. The region receives an average of 1,292 mm of rainfall each year, with the most precipitation happening in July and August months. Chhattisgarh can be geographically divided into three main zones: Northern Hills, Bastar Plateau, and Chhattisgarh Plains. The Northern Hills and Bastar Plateau areas are covered with natural forests, while Chhattisgarh Plains are primarily used for agriculture. The steep southwest sections of the Bastar Plateau are part of Central India's Satpura hills, specifically the Maikal Range. Chhattisgarh's forest cover comprises 12 distinct forest types, predominantly classified into two major categories: tropical moist deciduous forests and tropical dry deciduous forests (Champion & Seth, 1968). These forest types form the ecological backbone of the region, influencing biodiversity patterns, habitat availability, and ecosystem functions.

Methods

Data Analysis

The data of 218 elephant mortality cases over 23 years were collected from 19 divisional forest offices in Chhattisgarh, detailing incident locations, division name, date of the incidents, human fatalities and injuries (with gender). Surveys were conducted in conflict-affected villages, in collaboration with forest officials, to gather more precise and detailed information on incidents. For each mortality incidence, we standardised the categories of the data for: (1) the cause of death, (2) time of incident (year, month and season: monsoon, post-monsoon, summer and winter); (3) division-wise list; (4) age and demography of the dead elephant. The details of the causes of death were further recorded with additional classification (see Table 1). Elephant deaths brought by natural calamities and unprecedented accidents like drowning, lightning strikes, and falls from hills were included in accidental deaths. Age groups were categorised as calf (0–1 year), juveniles/yearlings (1–5 years), sub-adults male and female (6–15 years), and adult male and female (16+ years) (Arivazhagan & Sukumar, 2008).

Land use land cover change, and factors influencing elephant mortality

The satellite data spanned from 2000 to 2024 and were divided into five intervals: 2000–2005, 2005–2010, 2010–2015, 2015–2020, and 2020–2024. Land Use Land Cover (LULC) change analysis was performed using Landsat 5 TM and Landsat 8 OLI imagery, each with a spatial resolution of 30 m (Figure 2). Chhattisgarh falls within UTM Zone 46. Six bands (blue, green, red, NIR, and two SWIR) were used for classification, while the QA band was applied for cloud and shadow masking. We collected 1,250 random points for RF classifier training and validation, with 70% used for training and 30% for validation in each iteration. Accuracy assessment quantified classification effectiveness. Google Earth Engine (GEE) handled image

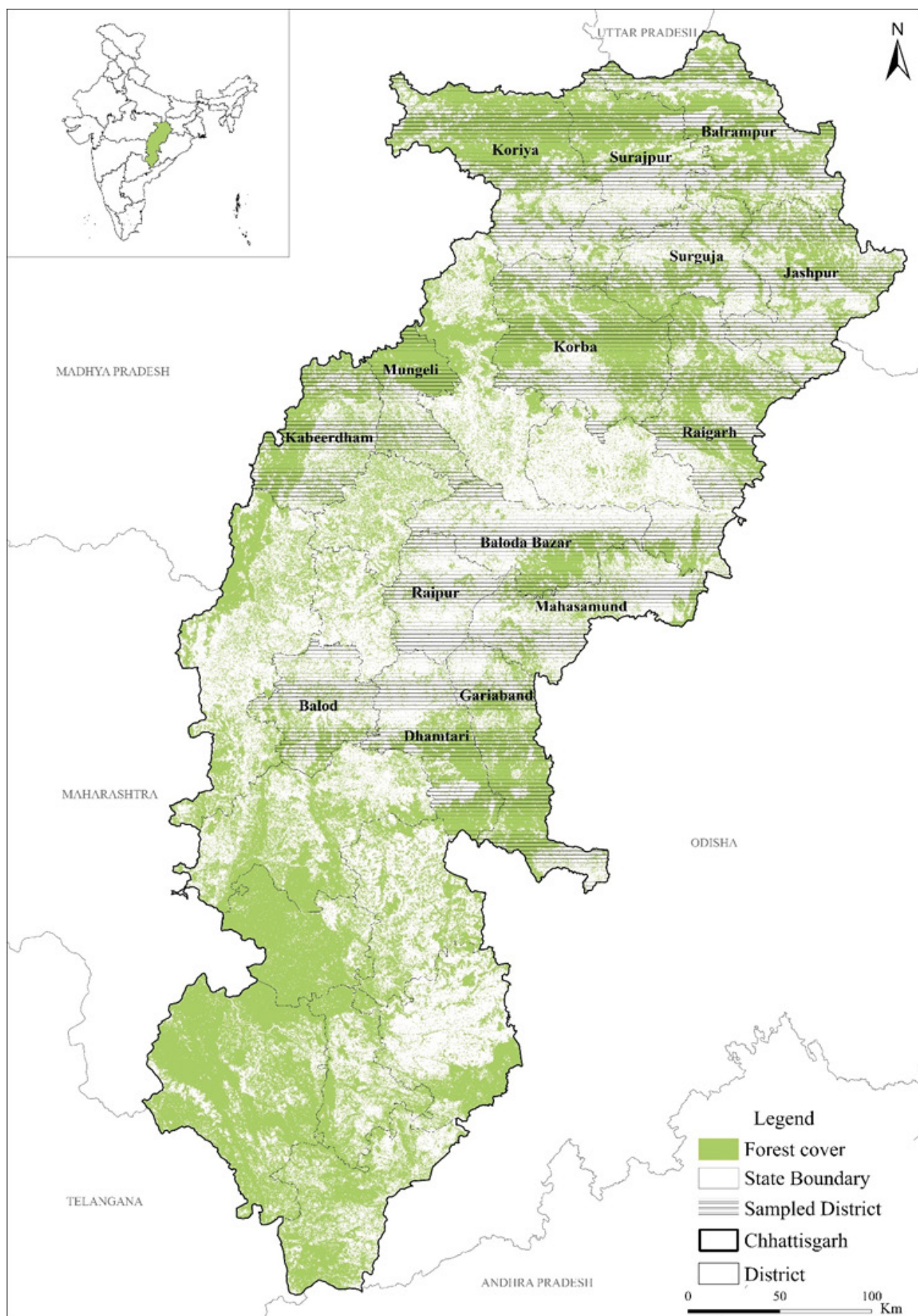


Figure 1. Map of Chhattisgarh State, India, showing forest cover and sampled districts. The map was created using ArcGIS Pro version 3.0.0 (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

Table 1. Causes of elephant deaths reported in the state of Chhattisgarh from 2000-2023

Causes of Elephant deaths	Indirect/ Direct sources	Categories
Still birth, old age, heart attacks, malnourishment, heat stroke, dehydration, illness	Natural	Natural
drowning, lightning strikes, fall from hills	Natural calamities, accidents	Accidental
Poisoning	Retaliation killing, HEC	Poisoning
Poaching	HEC	Poaching
Territorial fights	Natural behaviour, Interspecies conflict, decrease in territorial space	Territorial fights
falling into canals and wells, stuck in drains, electro-cution	Anthropogenic climate change, stress due to human infrastructures	Anthropogenic stressors

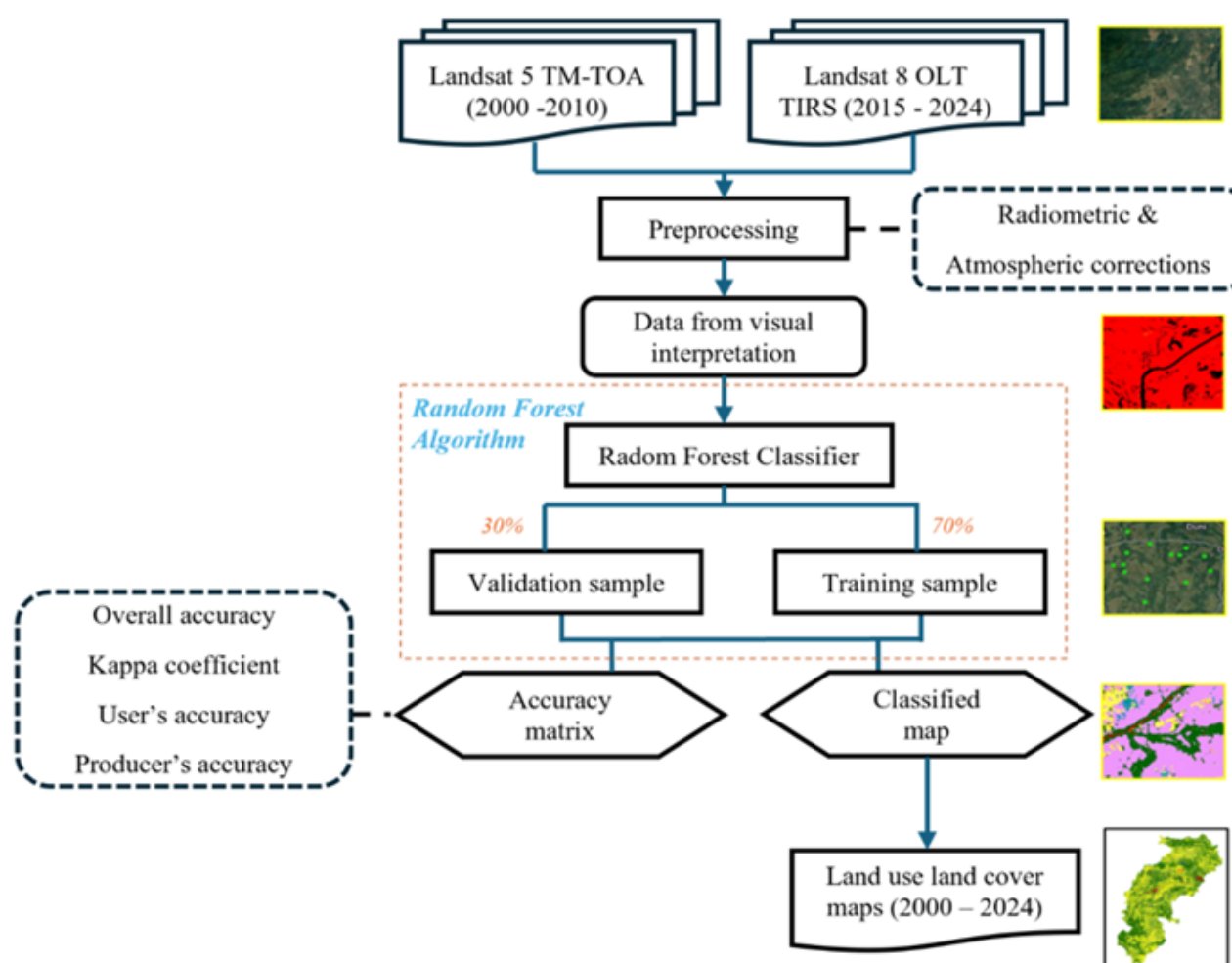


Figure 2. Flowchart of the methodology used to study the land use and land cover change pattern in the state of Chhattisgarh, India

processing and classification, while ArcGIS Pro was used for sub-setting, fragmentation analysis, distance calculations, and map preparation. A supervised pixel-based RF algorithm classified the Landsat dataset. The GEE was chosen for its robust accuracy and ability to handle large, high-dimensional datasets. RF classifiers applied to Landsat imagery in GEE effectively mapped five LULC categories: (1) forest, (2) water, (3) barren land, (4) agriculture, and (5) settlement. This study used the RF classifier from the “*smileRandomForest*” library. Using the forest cover class from the LULC maps, we extracted Patch Density (PD), Edge Density (ED), and Largest Patch Index (LPI) with FRAGSTATS v.4.2. A 7 km moving window analysis, based

on the average movement of elephants (Hassan *et al.*, 2023), was used to generate a continuous surface, ensuring ecologically relevant outcomes. The forest cover and fragmentation analyses in this study are based on remote sensing classification techniques and have not been field-verified due to the absence of ground reference points. Elephant death distribution was analysed with kernel density estimation in ArcGIS to identify mortality patterns across divisions and villages. Generalised linear models (GLMs) with a binomial distribution in R (version 4.3.1) were employed to predict the influence of ecogeographical and anthropogenic variables on elephant mortality incidents (excluding natural deaths). The occurrences of mortality were

coded as 1, while pseudoabsence locations (coded as 0) were generated using a two-step approach: (i) generating random points using the "Create Random Points" tool in ArcGIS Pro, and (ii) removing any points located within 1 km of a mortality incident to ensure they represented non-mortality zones. A total of 84 pseudoabsence points were retained after this filtering.

The GLM analysis included 12 explanatory variables: distances to forests, croplands, built-up areas, roads, railways, mines, waterways, protected areas, and elephant reserves, along with edge density, patch density, and largest patch index from *FRAGSTATS*, based on various hypotheses (Table 2). Model performance was evaluated using AIC, with models having $\Delta AIC \leq 2$ considered well-supported (Burnham & Anderson, 2002). Model selection was conducted through univariate analyses assessing the significance of each predictor, followed by collinearity checks to remove highly correlated variables ($VIF > 5$). We then developed multiple candidate models and evaluated them using the Akaike Information Criterion (AIC), retaining models with $\Delta AIC \leq 2$. Likelihood ratio tests were applied to compare nested models and assess predictor significance. The final model was selected based on the lowest AIC value and retained only significant predictors, ensuring an optimal balance between explanatory power and parsimony. The "MuMIn" package in R was used for model ranking.

Village categorisation for elephant mortality

To assess elephant mortality distribution in Chhattisgarh, we categorised villages into three groups: low (0–10 deaths), medium (11–20 deaths), and high (more than 20 deaths). This classification helped identify environmental factors influencing mortality, such as forest percentage, crop percentage, mines

percentage, water density, built-up percentage, and road and railway density. Understanding these patterns shall allow targeted mitigation efforts, focusing on high-risk areas for habitat restoration, conflict management, and infrastructure improvements.

Results

Land use land cover

The land use and land cover (2000 - 2024) changed in forest cover, water bodies, barren land, cropland, and built-up areas (Figure3). There has been a change of -7.26% in forest cover, with a change observed in 2005 (-2.47%), 2010 (-5.84%), 2020 (-1.02%), and 2024 (-1.76%). Urbanisation has shown an upward trend (Supplementary Table 1). The fragmentation analysis showed a high fragmentation in the northern and eastern regions of Chhattisgarh, with high edge density and patch density. Eastern areas have better forest connectivity with large continuous patches. The highly fragmented central part of Chhattisgarh faces a high risk of human elephant conflict (SF2).

Temporal and age demography

The long-term conflict records spanning over 23 years in Chhattisgarh resulted in a total of 218 elephant deaths attributed to multiple causes. Out of these, 134 were non-anthropogenic deaths, including natural cases (115 deaths), unknown (13 deaths), territorial fight (7 deaths) (SF1). While 84 anthropogenic causes included electrocution (76 deaths), poisoning (5 deaths), poaching (2 deaths), retaliatory killing (1 death), and vehicular accident (1 death). Electrocution emerged

Table 2. Factors Influencing Elephant Mortality in Chhattisgarh: A Priori Hypotheses

Feature	Variables	Source	A-priori Hypothesis
Landcover	Distance from Built-up (db)	Different landcover types (built-up, cropland, forest, waterbodies) are extracted from classified landcover data. Distance between conflict points and landcover were calculated using the Near Table tool (ArcPro 3.0.0).	Closer proximity to built-up areas may increase elephant mortality due to accidents, retaliatory killings, and habitat loss.
	Distance from Cropland (dc)		Higher elephant mortality is expected near croplands due to conflict arising from crop raiding and retaliatory actions.
	Distance from Forest (df)		Mortality may be lower near forests but increase at forest edges due to human-elephant interactions and habitat fragmentation.
	Distance from Waterbodies (dw)		Mortality risk may be higher near waterbodies, especially during dry seasons when elephants cluster around limited water sources, increasing human encounters.
Anthropogenic	Distance from Roads (dr)	Shapefile was obtained from Open-StreetMap and processed in GIS.	Proximity to roads may increase elephant mortality due to vehicle collisions and restricted movement corridors.
	Distance from Mines (dmn)	Mining areas were mapped using Google Earth Pro.	Mining areas may contribute to elephant mortality due to habitat destruction, pollution, and accidental falls into pits.
Protected Areas	Distance from Protected Areas (dpa)	Protected areas, Elephant Reserves were mapped using shapefiles from the Elephant Cell of WII.	Mortality may be higher at PA boundaries where elephants move into human-dominated landscapes, facing poaching or retaliation.
	Distance from Elephant Reserves (der)		Higher mortality may occur near reserves as elephants disperse into unprotected areas with human activity.

	Edge Density (ED)		Increased edge density may elevate mortality due to fragmented habitats forcing elephants into high-risk areas.
Landscape Metrics	Patch Density (PD)	Calculated using landscape metrics in FRAGSTATS.	Higher patch density may correlate with increased mortality by restricting movement and increasing conflict zones.
	Largest Patch Index (LPI)		Larger continuous patches may reduce mortality by offering safer movement corridors, while fragmented areas may heighten risks.

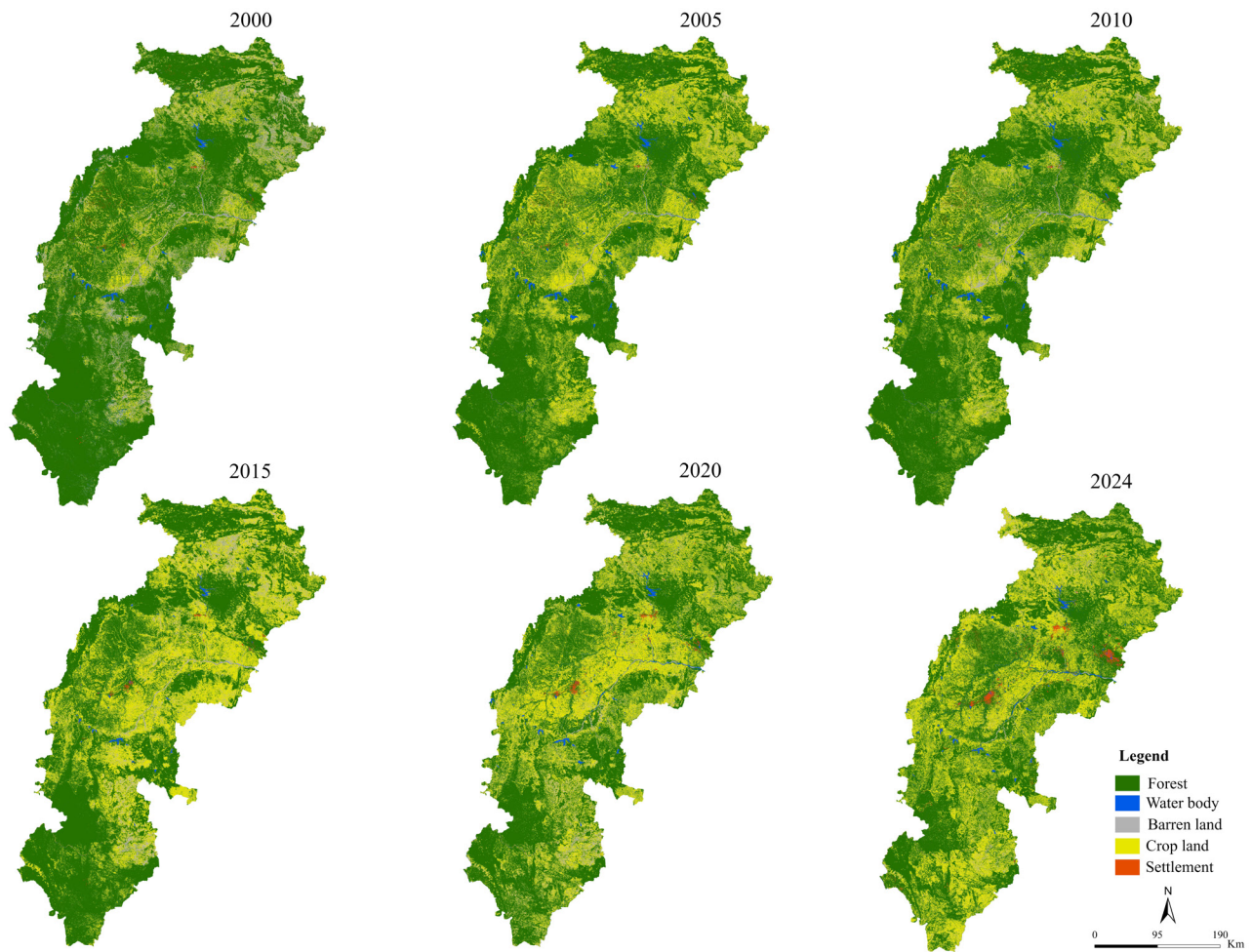


Figure 3. Land use land cover (LULC) maps of Chhattisgarh state, India, for the years 2000, 2005, 2010, 2015, 2020, and 2024. The maps were created using ArcGIS Pro version 3.0.0 (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

as the key reason for the elephant deaths, out of the anthropogenic causes ($\chi^2 = 11.468$, $df = 1$, p -value = 0.001; Figure 4). The number of death cases due to anthropogenic causes differed significantly across age and groups ($\chi^2 = 118.59$, $df = 5$, p -value < 2.2e-16), with adult males having the highest numbers of deaths (35), followed by adult female (17), sub adult male (13), sub adult female (4), yearling (5) (Figure 5). Among seasons, elephant deaths mostly occurred in monsoon season (26 deaths) ($\chi^2 = 5.101$, $df = 3$, $p = 0.164$), followed by post monsoon (20), winter (21) and the least deaths occurred in pre monsoon (12). Divisional variation showed that the highest elephant mortalities were observed in Dharamjaigarh (33 cases), with the most deaths occurring because of electrocution (33 cases), followed by Raigarh (11 cases; 8 electrocution cases), Jashpur (10; all electrocution cases), and Surajpur (9; all electrocution cases) (SF3). Kernel density estimation of the mortality represents the same (Figure6).

Village-level analysis of elephant mortality and its influencing factors

A total of 48 villages were identified where elephant mortality has occurred, with the most cases in Dharamjaigarh (15 deaths), followed by Chhal (10 deaths), Amandon and Goreapipar (4 deaths each), and Katghora and Raigarh (3 deaths each). High-incident villages had greater built-up density, while non-incident villages showed the lowest levels (Kruskal-Wallis Test: $\chi^2 = 8.8701$, $p = 0.0310$). Water sources remained relatively stable across all village categories ($\chi^2 = 7.981$, $p = 0.0463$). Cropland cover was substantially higher in high-fatality villages ($\chi^2 = 9.236$, $p = 0.02631$; Figure 7). Post-hoc Dunn's test revealed specific pairwise differences (Table 3). The road density ($\chi^2 = 7.1148$, $p = 0.06833$) approached significance, suggesting a potential trend but not meeting the conventional threshold.

Elephants' deaths were significantly influenced by habitat and human-induced factors, distance to cropland ($\beta = -1.237$, $p = 0.016$), and distance to elephant reserves ($\beta = -1.357$, $p = 0.001$).

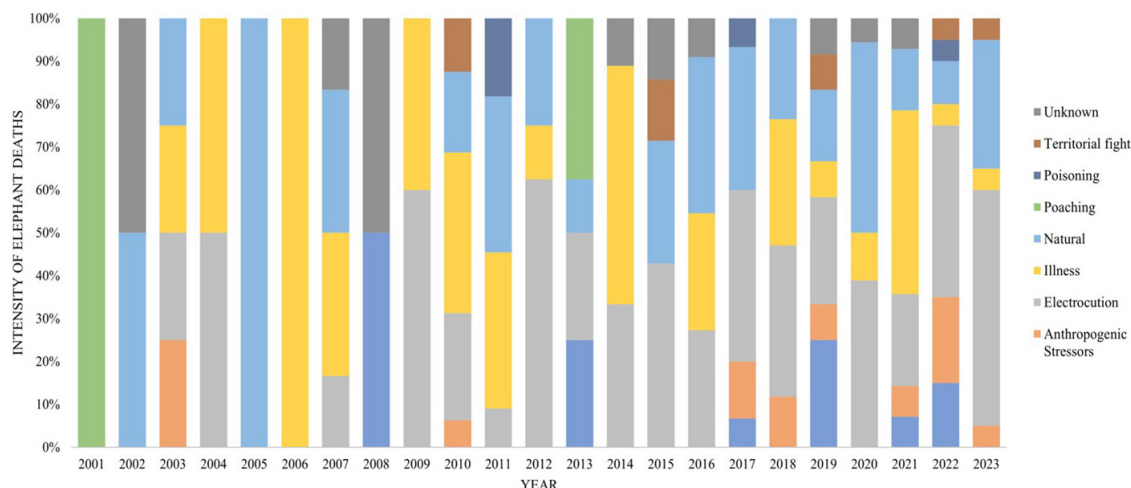


Figure 4. Temporal trends of elephant mortality 2000 to 2023 in Chhattisgarh, India

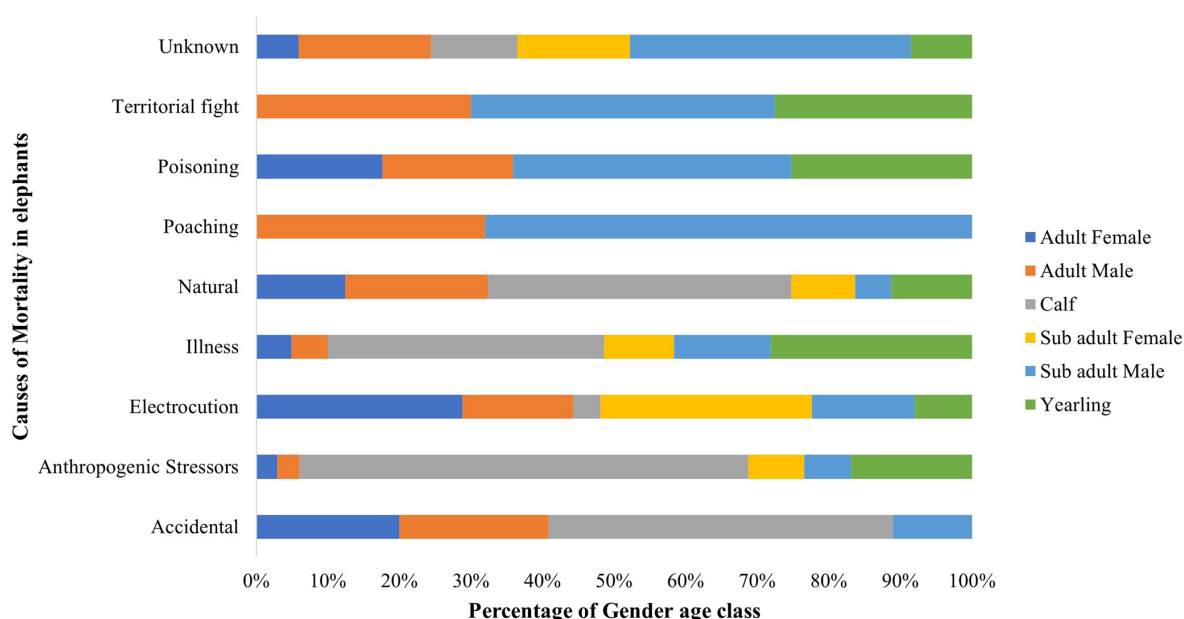


Figure 5. Age demography of elephants and its relation to different causes of mortality in Chhattisgarh, India (2000-2023)

Additionally, landscape features like the largest patch index ($\beta = -0.984$, $p = 0.001$) and edge density ($\beta = -0.676$, $p = 0.009$) showed significant negative relationships. Distance to built-up areas ($\beta = -0.461$, $p = 0.074$) and distance to mines ($\beta = -0.510$, $p = 0.064$) were marginally significant. Distance to forest ($\beta = 0.487$, $p = 0.031$), distance to protected areas ($\beta = 0.364$, $p = 0.182$) showed a positive trend. Distance to water ($\beta = -0.607$, $p = 0.096$), distance to roads ($\beta = -0.133$, $p = 0.594$) did not exhibit significant relationships with mortality risk (Table 4 & 5, Figure8).

Discussion

Our study on land use land cover highlights that deforestation and conversion of cropland to built-up areas over the last two decades could be one of the drivers of rising HEC in Chhattisgarh. The rapid expansion of coal mining, urbanisation, and linear infrastructure has fragmented critical elephant habitats and disrupted elephant movement pathways (Khan *et al.*, 2016). The east-central region, particularly Chhattisgarh, has the highest number of identified elephant corridors in India, totalling 52 (Pandey *et al.*, 2024), highlighting the extensive fragmentation of this landscape.

The situation is exacerbated by habitat mosaic complexity, mining expansion, and rapid infrastructure growth, leading to increased encounters and conflict-related mortalities (Natarajan *et al.*, 2023b). A significant portion of elephant range lies outside Protected Areas, in fragmented, human-dominated landscapes where the interspersed forests and croplands heightens conflict intensity. Sustainable land-use planning is both an ecological and socio-political necessity to ensure the conservation of elephants and the safety and livelihoods of local communities (Pandey *et al.*, 2024). LULC changes in Chhattisgarh reflect significant human-driven transformations, with a decline in forest cover, particularly in Korba and Raigarh, driven by expanding coal mines and urbanisation (Bhagat *et al.*, 2024). Deforestation threatens biodiversity, disrupts carbon sequestration, and reduces water availability, while the conversion of cropland into built-up areas raises concerns about food security (Khan *et al.*, 2016). Urbanisation, driven by population and economic growth, demands better land-use planning to balance development and sustainability. Similar trends have been observed in the Mahanadi River basin, with projections indicating a decline in grassland and an increase in croplands (Sahu *et al.*, 2024). Rapid urban expansion in Raipur has further contributed to the conversion of agricultural and open lands into built-up areas (Khan *et al.*, 2016). Henceforth, implementing sustainable land management strategies remains critical to address these emerging challenges effectively.

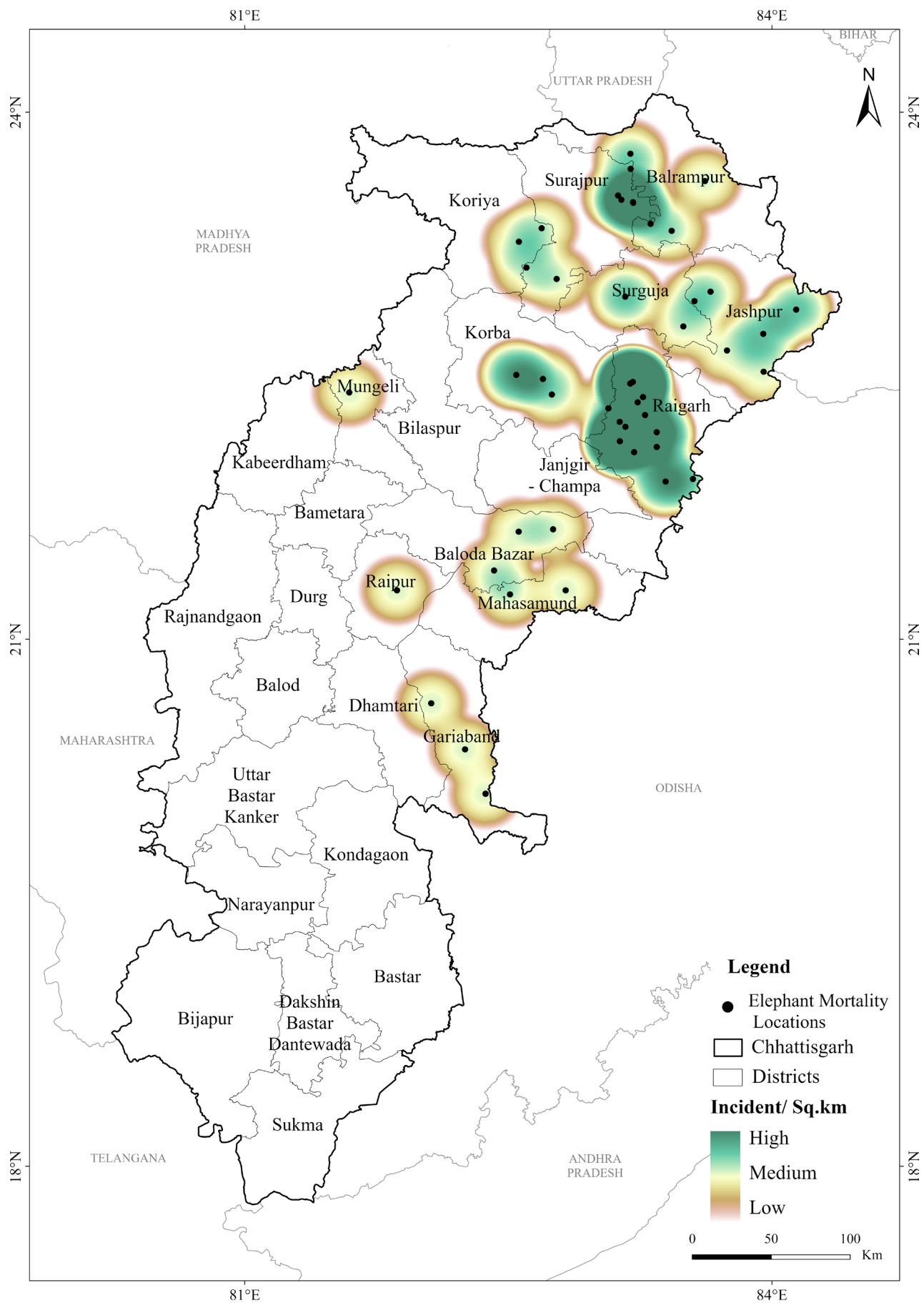


Figure 6. Hotspots of elephant deaths in Chhattisgarh State, India, from 2000 to 2023. The map was created using the kernel density tool in ArcGIS Pro version 3.0.0 (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

Table 3. Post hoc Dunn's Test for Significant Kruskal-Wallis Results

Variable	Comparison	p-value	Adjusted p-value
Water	Incident vs. Low Incident	0.0186	0.111
Built-up	Incident vs. Medium Incident	0.0146	0.0876
Crop	Incident vs. Medium Incident	0.0157	0.0944
Crop	Medium Incident vs. Low Incident	0.0245	0.147

Table 4. Summary statistics, log-likelihood (LogL), degrees of freedom (df), Akaike Information Criteria (AICc), relative support for hypothesis (Δ AICc), Akaike weights (Wi) of the candidate regression model explaining elephant mortality in Chhattisgarh.

Model	LogL	df	AICc	Δ AICc	Wi
dw + dr + df + dc + db + der + dpa + dmn + lpi + ed	-69.484	11	162.577	0.000	0.181
df + dc + db + der + dpa + dmn + lpi + ed	-71.842	9	162.767	0.190	0.165
dw + dr + df + dc + db + der + dpa + dmn + lpi + pd + ed	-68.857	12	163.629	1.052	0.107
df + dc + db + der + dpa + dmn + lpi + pd + ed	-71.363	10	164.060	1.483	0.086
dr + df + dc + db + der + dpa + dmn + lpi + ed	-71.435	10	164.204	1.627	0.080
df + dc + der + dmn + lpi + ed	-75.065	7	164.796	2.219	0.060
df + dc + der + dpa + dmn + lpi + ed	-74.024	8	164.910	2.333	0.056
dr + df + dc + db + der + dpa + dmn + lpi + pd + ed	-70.764	11	165.138	2.561	0.050
dc + db + der + dpa + dmn + lpi + pd + ed	-74.274	9	167.632	5.055	0.014
dw + dr + df + dc + db + der + dpa + dmn + lpi + pd	-73.023	11	169.655	7.078	0.005
df + dc + der + lpi + ed	-78.802	6	170.102	7.524	0.004
db + der + dpa + dmn + lpi + pd + ed	-77.028	8	170.918	8.340	0.003
der + lpi + ed + dmn	-80.811	5	171.976	9.399	0.002
der + dpa + dmn + lpi + pd + ed	-79.392	7	173.451	10.874	0.001
der + dpa + lpi + ed + dpa + dmn + pd	-79.392	7	173.451	10.874	0.001
null (Intercept only)	-121.983	1	245.988	83.411	0.000

Table 5. Parameter estimates effect (β) and probabilities of ecological and anthropogenic variables in determining the mortality of the Asian elephant due to various anthropogenic factors

Predictor	Beta	Z_value	P_value	Significance
(Intercept)	-0.378	-1.555	0.120	
Distance to waterbodies (dw)	-0.607	-1.663	0.096	.
Distance to roads (dr)	-0.133	-0.533	0.594	
Distance to forest (df)	0.487	2.152	0.031	*
Distance to croplands (dc)	-1.237	-2.413	0.016	*
Distance to built-up (db)	-0.461	-1.784	0.074	.
Distance to Elephant Reserves (der)	-1.357	-4.529	0.001	***
Distance to Protected Areas (dpa)	0.364	1.334	0.182	
Distance to mines (dmn)	-0.510	-1.852	0.064	.
Largest Patch Index (LPI)	-0.984	-3.616	0.001	***
Edge Density (ED)	-0.676	-2.599	0.009	**

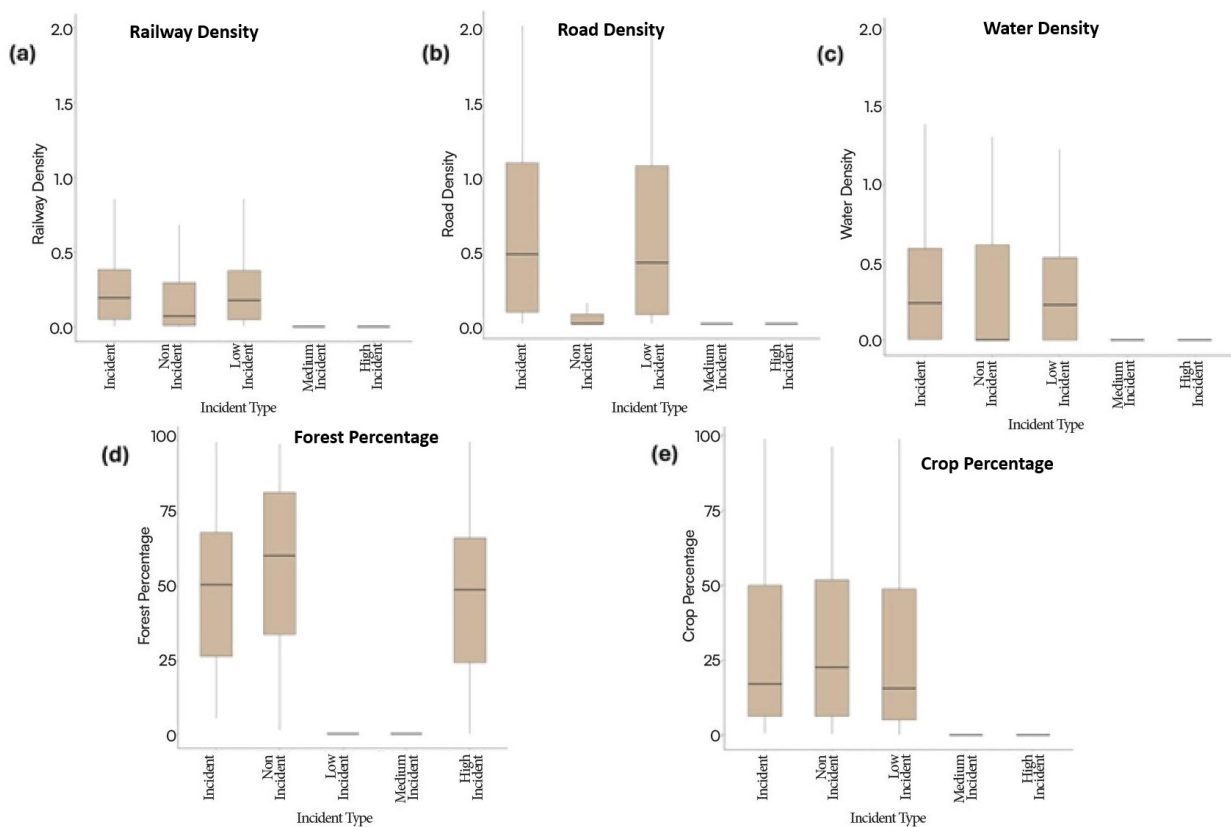


Figure 7. Box plot showing the built-up density, road density, railway density, crop percentage, forest percentage and mining percentage in non-incident, low-incident, medium-incident and high-incident villages in Chhattisgarh, India.

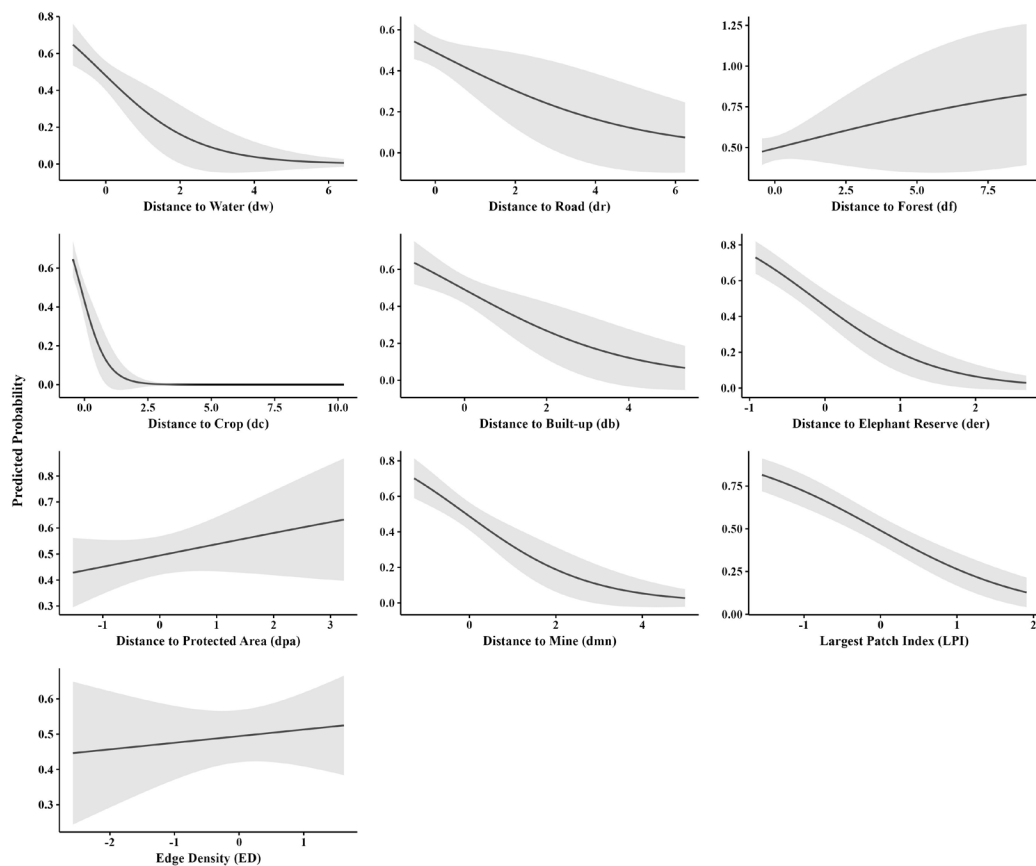


Figure 8. Graphs showing the probability prediction of elephant mortality in relation to the different selected variables in Chhattisgarh, India.

Furthermore, our findings highlight electrocution as the predominant cause of elephant mortality across divisions (in Chhattisgarh), particularly in areas with extensive electrical infrastructure. The concentration of fatalities in Dharamjaigarh, Raigarh, Jashpur, and Surajpur suggests a strong link between illegal fencing using distribution lines and, to some extent, sagging of power lines. Similar patterns have been reported elsewhere in India, where expanding settlements and poorly managed electrical networks heighten electrocution risk (Baskaran *et al.*, 2013; Gubbi *et al.*, 2014; LaDue *et al.*, 2012; Sangma *et al.* 2025). The highest number of elephant deaths due to electrocution reported from Dharamjaigarh could be linked to the widespread deployment of illegal electrical fencing surrounding agricultural fields in the area. A similar trend is also seen in other elephant landscapes in Tamil Nadu and Karnataka (Ladue *et al.*, 2012; Gubbi *et al.*, 2014).

Our study also showed that adult males experience the highest anthropogenic mortality, consistent with patterns observed in northern West Bengal (Roy *et al.*, 2017). This greater vulnerability is linked to male behaviour during musth, when they frequently enter human settlements or move along railway tracks, increasing the likelihood of fatal encounters. Habitat encroachment and expanding agriculture further compel elephants to forage in croplands, particularly during harvest seasons when raids peak (Pradhan *et al.*, 2013; Palei *et al.*, 2014). The loss of mature elephants, particularly socially dominant individuals such as matriarchs, can disrupt herd structure, cohesion, and decision-making (Douglas-Hamilton *et al.*, 2006). Adult elephants play a critical role in transmitting survival skills and guiding herd behaviour, and their absence can result in unpredictable behaviour, increased intra-herd aggression, and elevated human–elephant conflict. Studies have also shown that herds affected by culling or adult mortality exhibit social instability, whereas stable herds with intact social systems maintain cohesive interactions (Shannon *et al.*, 2013).

The current study showed that elephant mortality in Chhattisgarh was primarily influenced by both ecological and anthropogenic factors, consistent with earlier research on habitat fragmentation and human activity (Singh, 2002; Roy *et al.*, 2025). Across Asia and Africa, studies have linked habitat loss, fragmentation, and natural factors to increased elephant mortality and human–elephant conflict (Ladue *et al.*, 2021; Moeng *et al.*, 2022; Yu *et al.*, 2024). Agricultural expansion and urbanisation were key drivers of mortality, intensifying conflict as elephants were drawn to high-energy crops (Baskaran *et al.*, 2013; Shaffer *et al.*, 2019). Landscape metrics such as edge density (ED) and largest patch index (LPI) underscored the influence of habitat configuration, while distance to protected areas and water sources was less relevant due to elephants' wide-ranging movements. Infrastructure development, particularly mining and railways, posed emerging threats, with impacts varying by region (Chakraborty *et al.*, 2021). The near-significant link between road networks and mortality suggests that expanding infrastructure in elephant habitats could further elevate risks (Laurance *et al.*, 2009; Vanak *et al.*, 2010).

Conclusion

Over the past two decades, the elephant population in Chhattisgarh has increased, intensifying human–elephant conflicts driven by habitat loss, fragmentation, and electrocution. Major mortality hotspots such as Dharamjaigarh, Chhal, Amandon, Goreapipar, Katghora, Kunkri, and Raigarh highlight the urgent need to restore habitat connectivity and manage human activities. High-risk zones where elephants encounter power lines require immediate action, including

insulation and elevation of lines to 6–7 meters and regular maintenance. Promoting solar power can further reduce dependence on high-voltage infrastructure.

Habitat restoration, corridor maintenance, and early warning systems are key to minimising conflict. Community initiatives such as “Elephant Watch Groups,” compensation programs, and awareness campaigns can foster coexistence and reduce retaliation. Infrastructure measures like underpasses and overpasses, aligned with Wildlife Institute of India guidelines, ensure safe elephant movement across fragmented landscapes.

Technological innovations including AI-based predictive models, drones, satellite tracking, and smart collars with geofencing are transforming elephant management. Tools like the Gaj Sanket alert system, Elephant Tracking and Alert App, and Hathi Mitra Dal groups (Telegraph India, 2023; Down To Earth, 2022) have enabled real-time alerts and rapid response (The Hitavada 2022). Collaborative efforts with Kalpvig app have generated over two million alerts across 14 divisions, engaging 20,000 villagers and 5,000 officials, contributing to zero human casualties in Udanti–Sitanadi TR (Times of India 2024; NDTV, 2024).

Overall, integrating scientific tools, community engagement, and policy support provides a robust framework for mitigating human–elephant conflict. Sustained research, adaptive management, and technology-driven conservation are essential to ensure long-term coexistence between people and elephants in Chhattisgarh.

TO DOWNLOAD SUPPLEMENTARY MATERIAL [CLICK HERE](#).

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CONFLICT OF INTEREST

Bilal Habib & Parag Nigam hold editorial positions at the Journal of Wildlife Science. However, none of them participated in the peer review process of this article except as authors. The authors declare no other conflict of interest.

DATA AVAILABILITY

The data used in the study are available upon request from the corresponding author

AUTHOR CONTRIBUTIONS

Bilal Habib: Conceptualization (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (lead); Supervision (lead); Validation (lead); Visualization (lead); Writing-review & editing (lead). Ramesh Kumar Pandey: Conceptualization (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Supervision (lead); Validation (lead); Visualization (lead); Writing-review & editing (lead). Kalpana Roy: Data curation (equal); Formal analysis (equal); Methodology (equal); Writing-original draft (equal); Writing-review & editing (equal). Athira N. G: Data curation (equal); Formal analysis (equal); Methodology (equal); Writing-original draft (equal); Writing-review & editing (equal). Ananya Dutta: Data curation; Formal analysis; Methodology; Dheeraj Mittal: Data curation (equal); Investigation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing-review & editing (equal). Parag Nigam: Data curation (equal); Investigation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing-review & editing (equal). Anukul Nath: Data curation (equal); Investigation (equal); Formal analysis (lead); Methodology (equal); Resources (equal); Validation (equal); Writing-review & editing (equal).

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Navigating the coffee fields: elephants' use of habitat mosaics and the impacts of barriers on their spatial use of villages in a fragmented landscape of South India

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Abstract

Understanding the spatial ecology of Asian elephants (*Elephas maximus*) in fragmented landscapes is crucial for their management and for minimising human-elephant conflict. We studied elephants' use of habitat mosaics (forest fragments, monoculture plantations of eucalyptus and acacia, coffee plantations, agriculture, river backwaters, and other features – residences, roads, grazing lands, and open/rocky areas) and their intensity of presence in relation to physical barriers across 466 villages (1,180 km²) in the Hassan region of Karnataka between 2023 and 2025. Habitat selection analysis revealed a significant overall preference for monoculture habitats and forest fragments during both day and nighttime, despite their limited availability. This underscores their vital role, alongside forest patches, as refuge habitats for elephants navigating anthropogenic landscapes. Agricultural areas were generally avoided during the day but were moderately preferred at night. Coffee plantations were used in proportion to their availability throughout both day and night. Between 2010 and 2025, 277 solar-powered fences (32 km²) were constructed to prevent elephants from entering coffee plantations. The proximity of fences to habitat refugia limited elephants' access to resources, pushing them into new areas. Additionally, the widening of National Highway 75 has restricted elephant movement in a few villages, resulting in a gradual shift of elephant-intensive areas from south to north of the highway, pushing them into newer areas over three years.

Our study suggests protecting habitat refugia, redesigning fences, discouraging new fencing, and building overpasses on highways at elephant crossings to ensure safe movement and access to habitat refugia, thereby minimising human-elephant conflict.

Keywords: Asian elephant, habitat fragmentation, natural vegetation, solar-powered fences, village use intensity.

Introduction

The Asian elephant (*Elephas maximus*) is listed as an endangered species globally and is protected under Schedule I of the Indian Wildlife Protection Act of 1972, which provides the highest level of protection. It has been designated as the National Animal by the Government of India. As a habitat generalist, it holds symbolic significance in the religious and cultural spheres across Asia, and it continues to captivate audiences- from laypersons to researchers due to its magnificent appearance, intricate social structures, and its role as a flagship species in wildlife conservation. Asian elephants fulfil vital ecological functions as efficient seed dispersers across extensive ranges within their ecosystems (Campos-Arceiz & Blake, 2011). Nevertheless, habitat degradation, loss of natural habitats, agricultural expansion, and the diversion of forests for human development activities, including infrastructure projects, mining, hydroelectric projects, and plantations- continue to exert pressures on elephants both within and outside their natural habitats (Luo *et al.*, 2022; de Silva *et al.*, 2023). This situation poses a grave threat to elephant populations across their distribution, ultimately impairing their capacity to adapt to rapidly changing environments. Consequently, many elephant populations are fragmented and forced to inhabit human-dominated landscapes, resulting in conflicts between humans and elephants (Desai, 1991; Sukumar, 2006; Madhusudan *et al.*, 2015; Fernando *et al.*, 2019). Human development projects, such as hydropower stations and agricultural expansion, further fragmented elephant populations, disrupted population contiguity, and affected the safety and livelihoods of local communities (Leimgruber *et al.*, 2003; van de Water & Matteson, 2018; de La Torre *et al.*, 2019; Vasudev *et al.*, 2023). Despite cultural reverence in Asia, their numbers are declining due to reduced tolerance linked to these conflicts (Desai, 2000). Furthermore, forest loss resulting from the expansion of agricultural and commercial plantations, such as coffee and tea, has significantly impacted elephant movement and heightened human-elephant conflicts (Bal *et al.*, 2011; Kumar *et al.*,

2010; Puyravaud *et al.*, 2019). These fragmented environments often result in suboptimal habitats for large mammals, such as elephants, disrupting habitat connectivity (Xu *et al.*, 2021; Vasudev *et al.*, 2021).

The state of Karnataka, well known for its extensive biodiversity, harbours the largest population of elephants, estimated at around 6,000 (Qureshi *et al.*, 2025), representing one-fifth of the total Indian population (Baskaran, 2013). This population is distributed across three distinct groups, including regions within and surrounding the Bhadra Tiger Reserve, Shimoga, and the Hassan-Kodagu-Mysore-Mandya-Bangalore areas (KETF, 2012). The landscapes of Kodagu, Hassan, and Chikmagalur are characterised by significant alterations to natural habitats, primarily driven by agricultural expansion, particularly coffee plantations (Puyravaud *et al.*, 2019). This transformation has led to the creation of fragmented habitats, often described as “forest islands” amidst production landscapes (Mudappa & Raman, 2007). These islands provide critical resources for elephants but also pose challenges for their movement and access to food and water. Earlier studies indicated that there are around 470 elephants in the coffee-rice paddies-dominated landscape of the region (Baskaran, 2013). The population forms a continuous link between elephant populations in Nagarhole and the Kodagu side, and in the Bhadra Tiger Reserve in Chikmagalur, with plantation-agriculture-forest mosaics in between. Research indicates that Asian elephants in this region exhibit remarkable behavioural adaptations to navigate the challenges posed by anthropogenic landscapes (Bal *et al.*, 2011).

The Hassan Forest Division, adjoining the Kodagu Forest Division to the south and the Chikmagalur Forest Division to the north, has been considered an important area for connecting elephant populations between the Nagarhole and Bhadra Tiger Reserves. The Hassan region, primarily characterised by a mosaic of coffee and rice paddies, alongside forest fragments and monoculture habitats, supports approximately 55-65 elephants and nearly 2,50,000 people in 466 villages that experience intense human-elephant conflict in the form of loss or injury to human and elephant lives and crop damage caused by elephants (Baskaran, 2013; Appayya & Desai, 2007; Srinivasaiah & Sinha, 2012; Anonymous, 2023). Krishnan *et al.* (2019) highlighted the importance of remnant forest patches and monoculture plantations, such as Eucalyptus and Acacia, which serve as the only refugia and provide feeding and shelter for elephants. In this region, the conflict arises not only from crop damage and loss of human life but also from retaliatory actions taken by farmers such as elephant drives, resulting in injuries or deaths of elephants, besides exerting pressure on the state forest department to capture and remove elephants as a strategy to mitigate human-elephant conflict (Appayya & Desai, 2007; KETF, 2012). Furthermore, the presence of large-scale barriers such as solar-powered fences and railway barriers, and the expansion of the National Highway 75 (NH 75), influence elephants' use of fragmented habitat mosaics and their ranging patterns in relation to landscape changes, which remain understudied.

We investigated elephants' habitat preferences and intensive use of the landscape in relation to changes in the Hassan landscape over the years. The study aimed to address key objectives, including a. understand the elephants' use of fragmented mosaics of natural and anthropogenic habitats, b. analyse the spatial distribution of barriers in relation to elephant refugia, and c. spatial variation in the intensity of use by elephants across villages.

Materials and methods

Study Area

The study area comprised 466 villages (Figure 1), covering 1,190.5 km² across the Kodlipet-Alur-Sakleshpur-Alur-Arakalgud-Yeslur-Belur taluks, dominated by coffee plantations

on the upslopes and rice paddies grown in the fallow regions, which together account for 76 % of the study area (approximately 64,400 ha). Additionally, there are 42 monoculture plantations, such as Eucalyptus and Acacia, varying in size from 0.7 ha to 122 ha, 29 isolated forest fragments, and abandoned or non-functional coffee plantations (more than 20 years old) which play an important role as refugia for 55 – 65 elephants when they move through the production landscape (Krishnan *et al.*, 2019). In addition to elephants, the study area is frequently used by various species, including leopards, gaur, sambar deer, and mouse deer, which depend on these habitat refugia for movement. These refuge areas are distributed from north to south and northwest of the study region. The natural vegetation, in the form of forest fragments and Reserved Forest Areas, varies in size and collectively covers 5,240 ha. The Hemavati River, which flows through the middle of the study region and its backwaters, covering 3,224 ha, is a lifeline for people and elephants. While coffee is an annual crop, rice paddies are grown as a seasonal crop between July and December, during the southwest and northeast monsoons. Most of the coffee is owned by small and medium-sized growers, as well as a few national companies such as Tata Coffee Limited and Indian Builders Corporation Estate (IBC). The region receives about 300 cm of rainfall annually. The region supports around 2,00,000 people living in widely scattered villages and individual localities in plantations, mainly comprising coffee planters, paddy farmers, and maize growers, who also cultivate banana, areca, and pepper as intercrops. The inevitable dependence of people and elephants on land and resources, frequent negative interactions, and changes in landscape features posed significant challenges to coexistence between the protagonists.

Data collection

a) Elephant monitoring

Elephants were tracked daily through direct observations or indirect signs, such as dung, tracks, and feeding signs, for over three years, from 2023 to 2025. We have also relied on the state forest department field staff and an informant network across 466 villages to locate elephant presence and conflict occurrence in the study region. On each tracking day, information on age-sex composition, herd size, habitat type, name of the place or village and GPS coordinates of elephant locations at regular intervals along movement paths was systematically recorded. Once we located elephants during the day, we backtracked along their movement paths, using fresh dung, footprints, and feeding signs, to the location where they had been seen the previous day to record night locations (Kumar *et al.*, 2010; Krishnan *et al.*, 2019). All field data recordings were entered into a datasheet created using Epicollect, an open-source software (<https://five.epicollect.net/>), to improve data collection accuracy (Aanensen *et al.*, 2009; Center for Genomic Surveillance, 2026). Identification of elephants was carried out using photographs and physical markings such as ear shape, persistent lumps, cuts on the tail or ears and degree of ear folding. (Moss, 2006; Goswami *et al.*, 2007).

b) Digitising land use elements in the study region

The extent of natural and anthropogenic habitats, settlements, and physical barriers, such as solar-powered fences, railway barricades, and National Highway 75, was digitised using a combination of Survey of India topographic sheets, Google Earth imagery, and ground-truthing. Although the local village name was documented for each entry, we geographically linked the elephant locations to the official shapefile for Hassan district, supplied by the Karnataka State Government (<https://kgis.krsac.in/kgis/>), to obtain the corresponding administrative village name. Since some village names were similar, we modified them by adding numeric suffixes (1, 2, ...) for data analysis. This designation has been used throughout the results presented in the paper. Shapefiles were created and verified using GPS locations collected during fieldwork.

We used the Locus Map app (Asamm Software. Locus Map: Outdoor Navigation (Version 4.x) (Mobile app <https://www.>

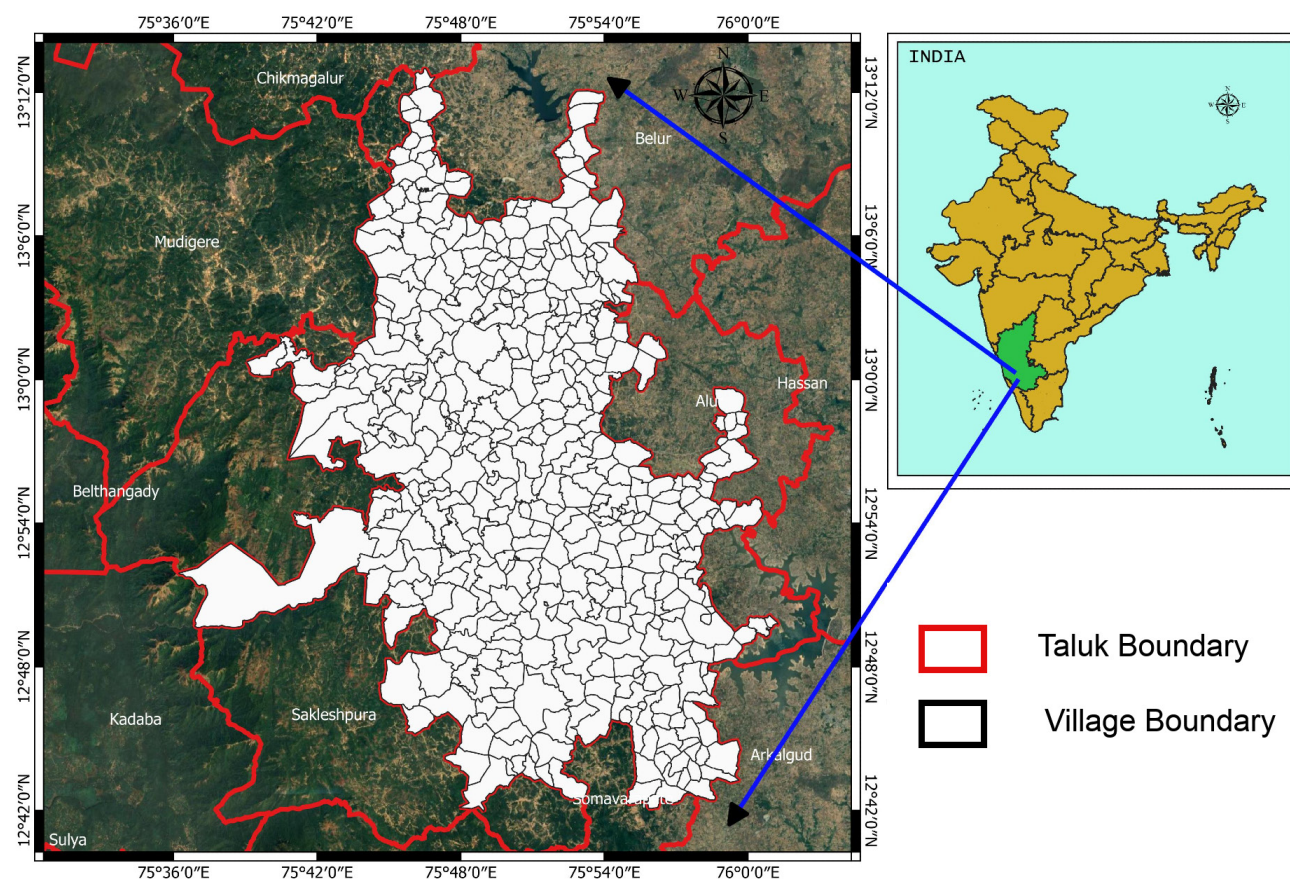


Figure 1. Location of the villages in Hassan district where elephant presence has been frequent

locusmap.app/) on smartphones to record the tracks of solar fences around coffee estates. Before recording the tracks for each fence, we obtained permission from the respective estate owners or managers to collect information on the date or month, and year of construction. Since installing fences is both costly and time-consuming, often taking several months, sometimes, the owners of the coffee estate might not have recalled the precise month, but were aware of the year of installation, particularly in the case of old fences that were constructed several years ago. In such instances, we have considered January of that year to be the month of fence installation. Then, we walked along the fences to generate vector layers. Subsequently, we used QGIS 3.34.3 (Q GIS Development Team, 2023) to create polygons for each fence and calculate their lengths, perimeters, and areas.

We have stratified the study area into six major habitat categories (Figure 2) including coffee (643.7 km², 54.07%), monoculture refuges such as acacia, teak, Eucalyptus, and abandoned coffee plantations which are more than 20 years old (7 km², 0.59%), agriculture (262.49 km², 22.05%) primarily dominated by rice paddies with other crops of maize, ginger, banana, coconut, areca, backwater area of Hemavati reservoir (32.24 km², 2.71%), natural vegetation areas of forest fragments and Reserved Forests (52.44 km², 4.4%) and others (townships, roads, residential clusters in villages, and livestock open grazing areas (192.65 km², 16.18%).

Data organisation

We analysed data spanning three years, from January 2023 to December 2025. Since the spatial locations of animals are inherently autocorrelated, we randomly thinned the data prior to any analysis. For each date, we randomly selected two locations (one daytime and one nighttime)

for each elephant ID (herds or males). We excluded locations of solitary male elephants that could not be identified in the field from subsequent analysis. We have examined one daytime and one nighttime location to analyse habitat use by elephants over a 24-hour cycle for each individual or herd ID, thereby minimising spatial autocorrelation.

The final data subset used for the analysis comprises 24,400 randomly selected locations that fell within the village boundaries of 466 villages currently being monitored for elephants. Of these locations, 53% were from the dry season, and the remaining were from the wet season (Ndry=12,981, Nwet=11,419). We had a near-equal split between day and nighttime locations (Nday=12,776, Nnight=11,624). Nearly 60% of locations were adult males or male groups (Nmales=14,647), and the remaining were herds (Nherds=9,753).

a) Seasonal Classification

We classified the months from January to June as the dry season and from July to December as the wet season. The seasonal classification included not only precipitation patterns but also the cropping patterns of the two major food crops, maize and rice, which are grown seasonally in the study area. To analyse rainfall patterns in the study area from 2023 to 2025, we used the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset to assess precipitation and identify seasonal periods. Paul *et al.*, (2024) reported that MSWEP shows the highest agreement with Indian Meteorological Department (IMD) rainfall data in the Western Ghats region of India. We therefore used MSWEP over the IMD gridded rainfall dataset because MSWEP has a higher spatial resolution (0.1°) than the IMD dataset's 0.25° (Paul *et al.*, 2024). The study area receives most of its annual rainfall from May to October (Figure S1), which influences the cropping pattern of food crops such as rice paddies and maize. Most villages towards the west, adjoining the Western Ghats, receive higher precipitation than those towards the east (Figure

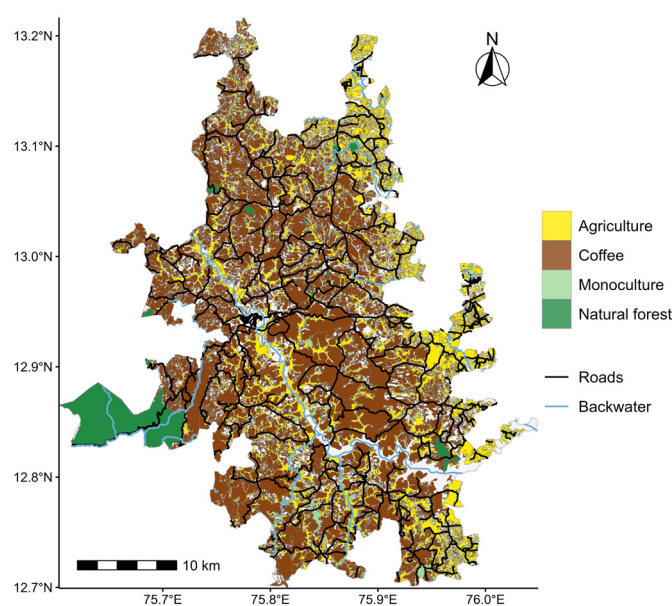


Figure 2. The distribution of six major habitat types, such as coffee, rice paddies, forest fragments, monoculture plantations, backwaters, and others, such as roads, residences, and grazing lands in the study region (left panel). An aerial image showing the predominant land use type of coffee on the upper slopes and rice paddy farming in the fallow regions in the study region (right panel).

S2). Farmers start sowing only at the end of June or early July, when sufficient rainfall has accumulated. Crop harvest begins in late November and continues until the end of December for rice paddies and maize, while coffee picking and pepper harvest last until March.

Data analysis

All data wrangling and statistical analyses were conducted using R statistical software version: 2026.01.1 (R Core Team, 2023). We used Manly's habitat selection analysis (Manly *et al.*, 1993) to examine how elephants use natural and anthropogenic habitats. This analysis measures habitat preference by comparing the proportions of locations in each habitat with the proportion of available habitat. A selection ratio of 1 indicates that a habitat class is used in proportion to its availability, whereas values greater than 1 indicate preference and less than 1 indicate avoidance. We conducted the analysis in three ways— using pooled data across all three years and splitting locations by day and night. We used the *adehabitatHS* package (Calenge, 2024) in R for the habitat analysis.

Elephant locations were spatially intersected with the village-level shapefile to identify the administrative villages associated with each location, using the *sf* package (Pebesma, 2018; Pebesma & Bivand, 2023) in R. We aggregated the total number of locations within each village for each season within each year to obtain the total count of elephant locations. This count was further scaled by the total area of the village to obtain village-level density or intensity of elephant use. We ran a Getis-Ord (G_i^*) analysis (Getis & Ord, 1992) to identify spatial clusters of elephants' use intensity in villages. This method uses both the feature value and the values of neighbouring features to identify spatial clusters of hot and cold spots. It generates a standardised z-score (G_i^* z-score) centred on 0, with positive values indicating hotspots and negative values indicating cold spots. Since the z-score is centred on 0 (mean=0), it can be used to identify statistically significant clusters at $z=\pm 1.96$ ($p<0.05$) and $z=\pm 2.576$ ($p<0.01$). This analysis was implemented using the *spdep* package (Bivand & Wong, 2018) in R. We defined neighbours based on Queen's contiguity method, i.e., neighbouring villages share either a common boundary or a common vertex (in contrast to Rook's contiguity method, which assumes neighbours share only a common border).

To understand the spatial distribution of solar fences, we calculated the nearest (Euclidean) distance from each fence polygon to the nearest refuge polygon (monoculture or natural vegetation patches).

Results

Habitat selectivity by elephants

Manly selectivity ratios from pooled data indicated an overall preference for monoculture plantations (Manly selectivity index: $w_i=13.24$, $S.E.=0.29$, $p<0.001$) and natural vegetation (forest fragments; Manly selectivity index: $w_i=4.24$, $S.E.=0.06$, $p<0.001$). Coffee, being the dominant land use type in the study area, was used proportional to its availability in the landscape ($w_i=1.02$, $S.E.=0.02$, $p<0.001$) whereas other land use types of agriculture ($w_i=0.63$, $S.E.=0.01$, $p<0.001$), backwater ($w_i=0.38$, $S.E.=0.02$, $p<0.001$) and other habitats ($w_i=0.22$, $S.E.=0.007$, $p<0.001$) were avoided (Figure 3(a), Table S1a).

Selectivity of habitats by elephants during the day mirrored overall patterns, with strong positive selection for monoculture patches ($w_i = 19.89$, $SE = 0.48$, $p < 0.001$) and natural vegetation fragments ($w_i = 6.68$, $SE = 0.09$, $p < 0.001$), with near proportional use of coffee ($w_i = 1.01$, $SE = 0.008$, $p > 0.05$), and avoiding agriculture ($w_i = 0.01$, $SE = 0.002$, $p < 0.001$), backwater ($w_i = 0.006$, $SE = 0.004$, $p < 0.001$), and other habitats ($w_i = 0.25$, $SE = 0.01$, $p < 0.001$; 9 (Figure 3(b), Table S1b).

At night, elephants exhibited a high positive preference for monoculture patches ($w_i = 5.94$, $SE = 0.29$, $p < 0.001$), natural vegetation ($w_i = 1.56$, $SE = 0.05$, $p < 0.001$) and agricultural fields ($w_i = 1.32$, $SE = 0.02$, $p < 0.001$) while coffee was used almost in proportion to its availability ($w_i = 1.03$, $SE = 0.009$, $p < 0.001$). In contrast, elephants showed a significant avoidance of backwater areas ($w_i = 0.788$, $SE = 0.05$, $p < 0.001$) and other habitats such as residential localities, roads, and open grazing lands ($w_i = 0.19$, $SE = 0.01$, $p < 0.001$; Figure 3(c); Table S1c).

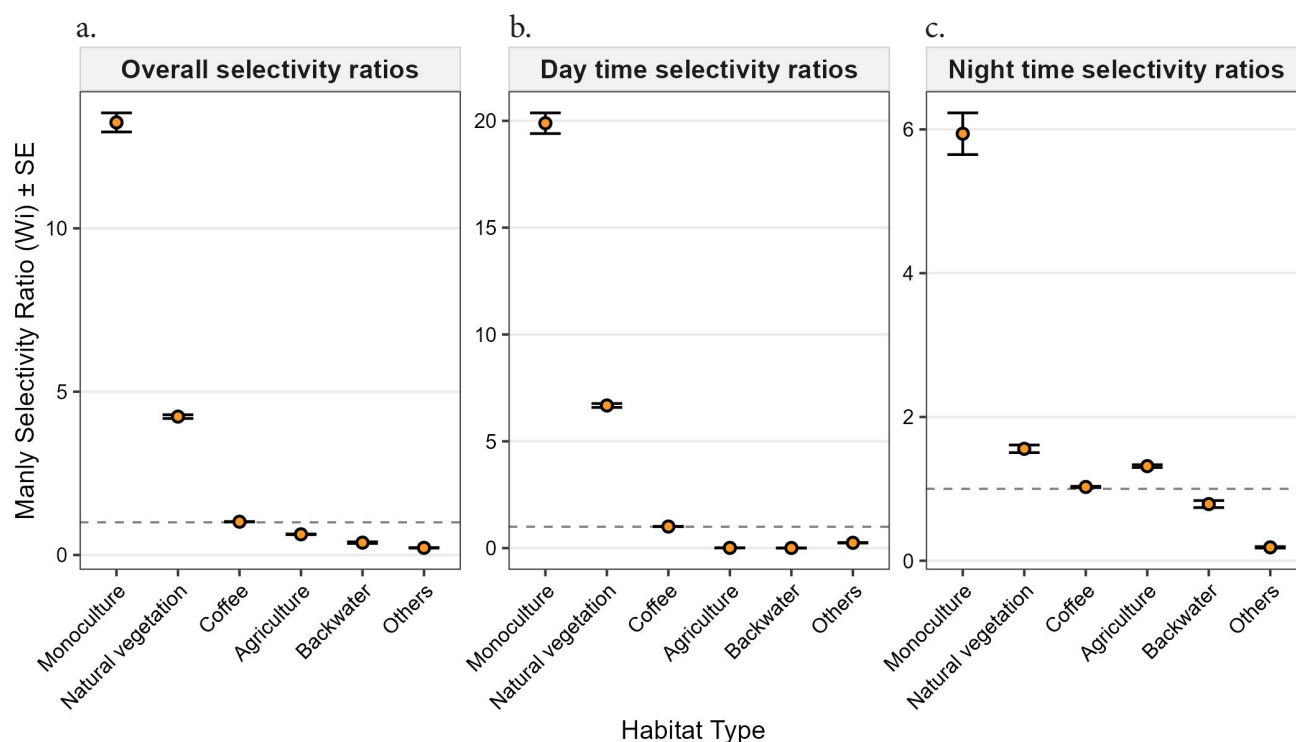


Figure 3. (a) Overall selectivity of major habitats by elephants in the Alur-Sakaleshpur-Yeslur-Belur region of Hassan as indexed by Manly Selectivity Ratio (w_i) with 95% confidence intervals. (b & c) Day and nighttime habitat selectivity, indexed by Manly selectivity ratios (w_i), with 95% CI in the Hassan region. Data analysed for the period 2023-25 from pooled random locations.

Solar fences: proliferation and spatial patterns

The number of solar-powered fences around coffee estates in the study region has gradually increased over the years (Figure 4). We have mapped 277 solar-powered fences, with a cumulative length of 382 km, covering 32 km² (~5% of the total study area), installed around plantations between 2010 and 2025 to prevent elephants from entering coffee estates (Table 1). Most of the fences have been installed in the north-south direction, aligned with the distribution of monoculture refugia and forest fragments (Figure 4). Over the past decade, we have witnessed an 886% increase in the areas protected by solar fencing.

The Euclidean distance to the nearest solar fence from each refuge fragment underscores the increased proximity of solar fences to these fragments, with a range of 0-13 km and a mean of 1.31 ± 2.68 km (SD). Nearly 20% of all refuge fragments share a border with a solar fence, while an additional 30% have fences located within 300 meters (median = 0.31 km).

Hotspot Cluster analysis of the village-level use intensity of elephants

Village-level spatial hotspots of elephant use intensity were identified using the Getis-Ord G_i^* analysis (Figure 5). There were no “cold spots” in the landscape, indicating that most villages experienced elephant use proportional to the village area. We identified the hotspot villages, which exhibit seasonal fluctuations between the dry and wet seasons. In 2023, the highest-use villages (hotspot villages) were distributed on either side of National Highway 75 in the Alur-Sakleshpur range. In 2024, hotspot villages were shifted to villages north of the highway in the Sakleshpur-Belur range. This pattern of intensive use of villages in the northern side of the study area, continues into 2025, with a noted reduction in the total number of identified hotspot villages in the recent period.

During the 2023 dry season, elephant locations were recorded across 224 villages, with 40 villages showing significantly higher elephant densities. These villages were located on either side of the national highway. Similarly, in the following wet season, 53

villages emerged as hotspots of elephant presence among the 239 villages used by elephants. These hotspot villages were spread across both sides of NH-75 and extended into the eastern region.

In 2024, during the dry season, elephant sightings were recorded in 209 villages, of which 50 were identified as spatial hotspots. Most of these hotspots are situated to the north and northwest of NH-75, with only four hotspot villages located south of the highway. During the wet season of 2024, all 34 hotspot villages out of a total of 215 elephant-occupied villages were found north of the highway.

In 2025, a pattern similar to 2024 was observed, with hotspot villages primarily located north of the highway in both the dry and wet seasons. During the dry season, 34 of the 174 villages had significantly high elephant activity. In the wet season, 31 of 149 villages were intensively used by elephants.

Discussion

The Asian elephant (*Elephas maximus*), a habitat generalist species, demonstrates a remarkable ability to adapt to varying ecological conditions and modify its behaviour accordingly. However, the persistent challenges posed by fragmented habitat mosaics, primarily dominated by human activity, raise significant concerns about elephant survival in altered landscapes. In the Hassan region, the predominance of coffee and rice paddies, juxtaposed with forest remnants, monoculture habitats, and human habitations, creates a complex landscape that complicates elephants' use of fragmented mosaics and movement.

Despite the limited availability of natural forest patches and monoculture plantations such as Acacia and Eucalyptus refugia, which comprise less than 7% of the total landscape in the study area, these refugia played a critical role in elephant movement. Overall, elephants preferred forest fragments and monoculture

Table 1. Annual patterns statistics of total solar fence coverage in the study areas, along with year-to-year percentage increase between 2010 and 2025.

Year	Fence area (km ²)	Cumulative fence area (km ²)	Length of the fence (km)	Cumulative length of fences (km)
2010	0.12	0.12	1.8	1.8
2011	0.08	0.19	1.5	3.3
2014	0.49	0.69	7.4	10.7
2015	2.58	3.26	16.1	26.8
2016	4.73	7.99	51.3	78.1
2017	2.58	10.58	29.1	107.2
2018	2.73	13.31	20.3	127.5
2019	0.77	14.08	16.1	143.6
2020	4.69	18.77	34.2	177.8
2021	2.65	21.42	24.0	201.8
2022	2.27	23.68	28.0	229.8
2023	4.49	28.17	63.5	293.3
2024	3.43	31.60	72.0	365.3
2025	0.58	32.18	16.7	382.0

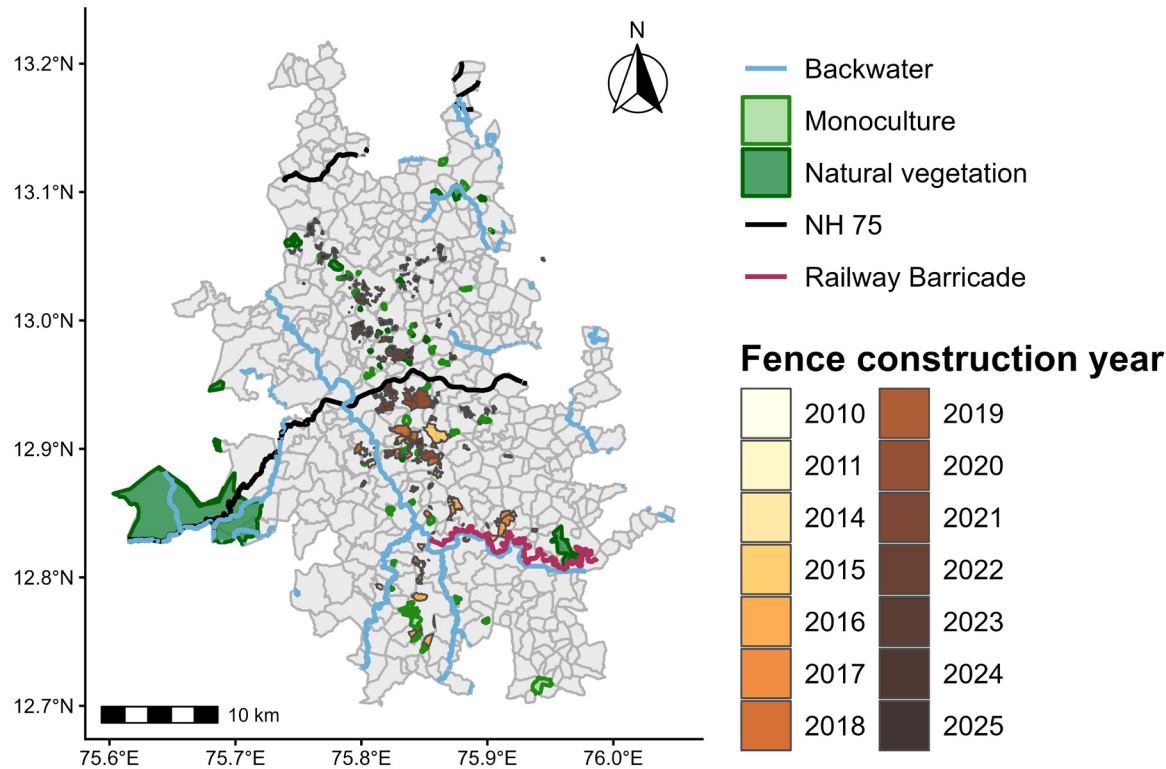


Figure 4. Locations of a railway barrier (pink line), the National Highway 75 (black line), and solar-powered fences that have been installed gradually around coffee plantations between 2010 and 2025 (different colours for different years) in relation to the distribution of monoculture plantations such as *Eucalyptus*, *Acacia*, and abandoned coffee plantations (light green) and forest fragments (dark green)

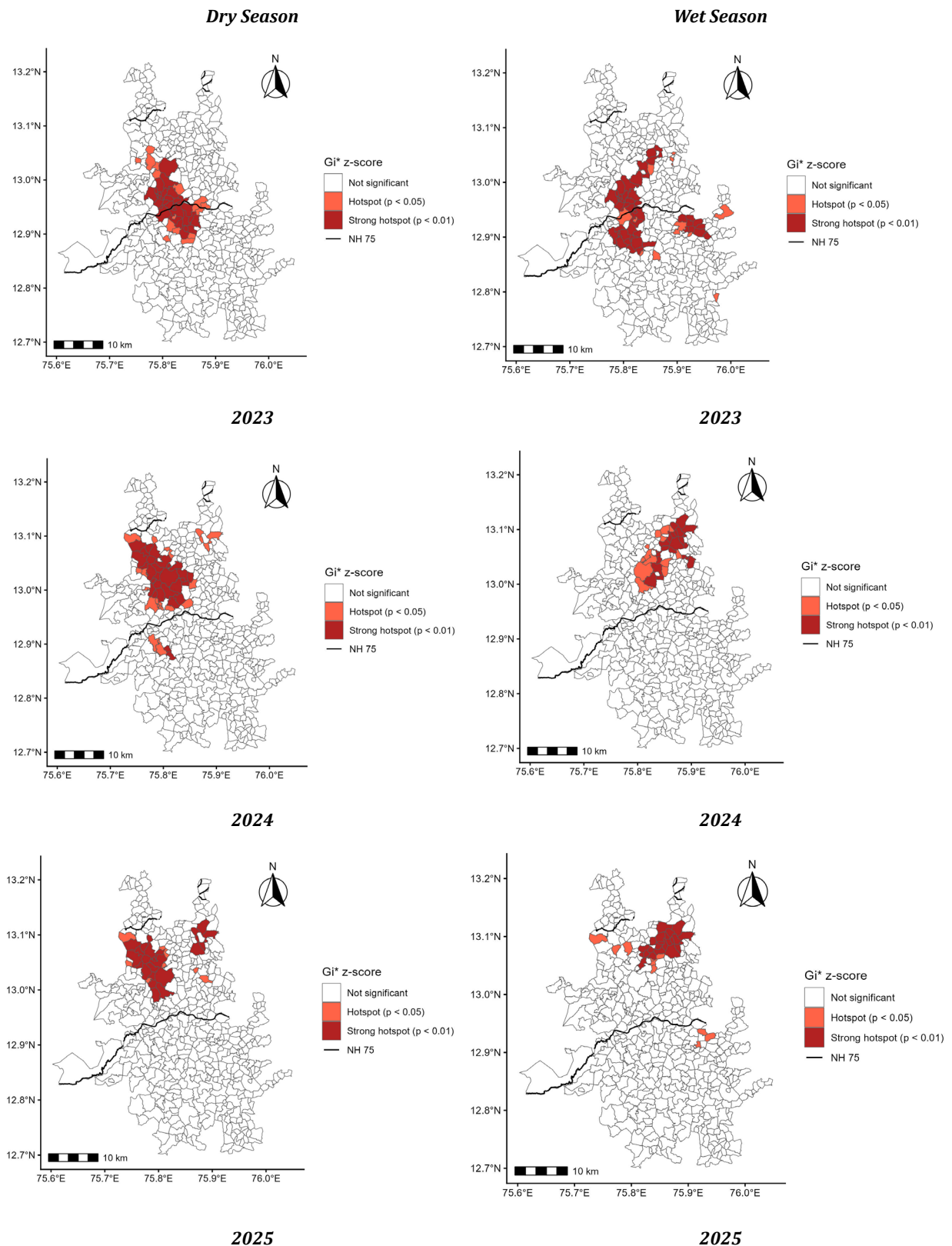


Figure 5. Spatial clusters of hotspot villages with the highest elephant activity across seasons, identified among the 466 monitored villages in the Hassan landscape from 2023 to 2025.

refugia that served as both shelter and feeding grounds, while coffee use was proportional to its availability. In contrast, agricultural habitats, backwater habitats, and village premises were largely avoided, highlighting the species' avoidance of human-dominated areas.

Elephants' use of different habitat classes showed moderate diurnal variation and mirrored the overall pattern. Elephants exhibited a strong preference for monoculture plantations and natural forest fragments, with a disproportionately higher number of elephant locations in these habitat classes, despite their relatively small land area and patchy distribution. Even though selection strength decreases at night, these patches remain highly preferred compared to other land-use classes. Agricultural fields are avoided during the day ($W_i=0.011$) but remain moderately preferred at night ($W_i=1.32$). Coffee plantations that dominate the landscape were used in proportion to their availability during both day and night, owing to the presence of grass and water resources that attract elephants (Bal *et al.*, 2011). However, elephants avoided the backwater area of the Hemavati Reservoir and other land-use classes, such as residential areas, roads, and open grazing lands, probably as a strategy to avoid risks associated with habitations and sand mining activity at night in the backwater areas, as elephants tend to alter their behaviour by swiftly moving through human-dominated landscapes between areas of tree cover (Graham *et al.*, 2009; Fernando *et al.*, 2023).

The B_i (standardised W_i ratio) values estimate the relative contribution of each habitat category, which allows us to rank habitat classes in order of preference (see Table S1). With six habitat classes in our analysis, a $B_i = 1/6$ (0.167) indicates a neutral preference, meaning elephants were distributed among these land-use classes in proportion to their availability (Manly *et al.*, 2002). Across all three analyses — overall, daytime, and nighttime — our findings underscore the importance of habitat refugia, such as monoculture plantations and forest habitats, which help elephants navigate anthropogenic habitats. Even during the night, we observed an increase in B_i values for coffee and agricultural habitats ($B_i=0.10$ and 0.12 , respectively), alongside a corresponding decrease in the intensity of use of natural vegetation patches ($B_i=0.14$); monoculture remained the most preferred habitat class ($B_i=0.55$). The software package used in the analysis does not generate confidence intervals (CI) for the B_i values, limiting further inferences about elephants' use of the coffee, agriculture, and natural vegetation classes at night.

The findings from this study corroborate our earlier research on elephant habitat preferences from the Alur-Sakhleshpur-Kodlipet region of the Hassan landscape (Krishnan *et al.*, 2019). Similar patterns have been observed in the tea-plantation-dominated Valparai region, where natural vegetation and riverine habitats are essential to sustaining elephant populations, while anthropogenic habitats are predominantly used at night for movement (Kumar *et al.*, 2010). This behaviour enhances their survival in fragmented landscapes, reflecting adaptive strategies in response to environmental and habitat changes (Fernando *et al.*, 2008; Neupane *et al.*, 2019; Pokharel & Sharma, 2026). In the study area, although the proportion of monoculture plantations is lower than that of forest habitats, their north-south distribution and the availability of secondary vegetation and shade influenced elephants' use of these habitats and their movements through anthropogenic habitats. Monoculture refugia scattered across the landscape are forest department lands; hence, they are relatively undisturbed with minimal human presence and vehicular disturbance. Furthermore, these plantations have abundant secondary vegetation such as bamboo, which is planted by the Forest Department and provides foraging opportunities for the elephants.

The predominant orientation of forest fragments and monoculture refugia—primarily north-south and westward—has significant implications for elephant movement across the study area. Therefore, it is imperative to establish connectivity

between these fragmented habitats wherever feasible to facilitate unhindered movement of elephants. In scenarios where physical connectivity proves unattainable, collaborative efforts with local coffee planters and paddy farmers should be initiated to promote functional connectivity between refugia. Such measures will not only enhance elephant movement but also help mitigate human-elephant conflicts in the region (Vasudev *et al.*, 2023).

Over the years, land-use changes were observed between 2010 and 2025, during which a large number of solar-powered fences, a 35 km stretch of rail barricades along the Hemavati Reservoir backwaters, and the expansion of National Highway 75 from two-lane to four-lane impacted elephant movements. Solar-powered fences were installed around coffee plantations to deter elephants from entering the estates. Studies have highlighted the adaptive responses of elephants to the specific spatial arrangement of natural and plantation forests within mosaic habitats, as the distribution of food and water resources, along with barriers and patterns of human activity over time and space, shape their ranging and foraging behaviours (Alfred *et al.*, 2012; Kanagaraj *et al.*, 2019; Ram *et al.*, 2024; Mimeault & Weladji, 2025). The inability of elephants to exhibit wide-ranging movements could trigger ecological cascading effects, and their movement systems are highly dependent on specific bottlenecks that are increasingly threatened by human activities in fragmented elephant landscapes. Elephants tend to adapt their movements in response to resource availability in specific habitat patches, often choosing paths that maximise foraging efficiency while minimising conflict with human activities (Fernando *et al.*, 2008). Thus, understanding elephants' forage selection in human-dominated landscapes is critical, as it enables managers to prioritise habitats, secure forest resource areas, and reduce human-elephant conflicts.

In the Hassan region, most of these fences were spatially oriented north-south and towards the northwest, in accordance with the spatial distribution of forest remnants and monoculture refugia. Between 2010 and 2025, 277 fences of varying sizes around coffee plantations gradually appeared, covering approximately 32 km², representing an overall per cent increase in fence length of 21,122% over this period. The majority of these fencing structures are located near critical refuge areas, significantly limiting elephants' access to these vital habitats and resources.

The spatial configuration of fences significantly affected their habitat use and movement throughout the study region. As a result, there was a shift in elephant movements and the intensity of village use over the years, with a higher concentration of elephant locations towards the north and northwest, rather than across the study area (Krishnan *et al.*, 2019). Such land-use modifications not only affect elephants' habitat preferences but may also drive them into neighbouring areas, heightening the potential for human-elephant conflict (Fernando *et al.*, 2015; Osipova *et al.*, 2018).

Moreover, the presence of solar fences around coffee plantations may compel elephants to use roads and residential or village premises, increasing the likelihood of encounters between people and elephants in the Hassan region. The presence of calves or young elephants may force herds generally to avoid areas with fences. Conversely, male elephants are known to navigate risks by breaking fences when moving between natural and human-altered habitats. These alterations in elephant movement patterns present significant challenges for effective management and conservation strategies, while also shifting conflict dynamics to areas where local communities may lack the experience to handle such interactions. Moreover, confinement to limited habitats can lead elephants to forage in closer proximity to human settlements, resulting in habituation to human presence (Vanak *et al.*, 2010).

The conversion of National Highway 75 from a two-lane to a four-lane road (commenced in 2019 and completed in 2023) has further fragmented elephant populations and restricted their

access to habitats and movement in villages located to the north of the highway. By 2023, elephants were found on both sides of the highway. However, in 2024 and 2025, elephant use intensity in villages shifted to the north of the highway. Though elephants were seen in most villages, their intensive use was observed in a few. Over the years, elephants showed distinct seasonal patterns of village use. During the dry season, hotspot villages were primarily observed on the western side, where large coffee estates provided adequate grass and water resources, as well as shelter for elephants (Bal *et al.*, 2011). During the wet season, the intensity of elephant presence in villages shifted largely to the east, due to the presence of seasonal crops such as maize and rice paddies, resulting in increased human-elephant conflicts. Local cropping patterns are contingent on rainfall patterns, which in turn influence elephant movement and determine crop loss incidents within the region (Webber *et al.*, 2011; Bohrer *et al.*, 2014; Anoop *et al.*, 2023; Matsika *et al.*, 2024). The onset of early rains enables farmers to commence planting; however, the subsequent harvesting period after the peak rainy season tends to attract elephants to agricultural fields, thereby exacerbating human-elephant conflict (Webber *et al.*, 2011; Matsika *et al.*, 2024).

Conclusions

The results of the study highlight the need to manage elephants in fragmented landscapes, grounded in an ecological understanding of their behaviour and navigation through anthropogenic habitats. Given that most Asian elephants occur outside protected areas (Madhusudan *et al.*, 2015), identifying critical habitats is essential for elephant management in fragmented landscapes. In the Hassan region, despite low coverage and distribution of natural forests and monoculture habitat refugia, they played a significant role in elephants' habitat preferences and facilitated their movement. Hence, protecting these habitats and preventing their conversion to some other land uses is extremely important for the survival of elephants and for minimising conflicts. Given the large-scale degradation and loss of habitats suitable for elephants across their distribution ranges, many elephant populations have been ranging outside PA boundaries in anthropogenic landscapes, with complex behavioural adaptations that modulate their group dynamics (Srinivasaiah *et al.*, 2019), time-activity budgets, and vocal repertoire (Pokharel & Sharma, 2026).

The installation of solar-powered fences around coffee plantations in key locations adjacent to critical elephant habitats has hindered elephant movement, pushing them into neighbouring areas. This has led to an increase in crop damage incidents and poses a significant threat to human safety. Therefore, it is imperative to avoid fencing large coffee plantations near natural forests and monoculture plantations, as this impedes elephants' access to refugia and essential resources. In areas with existing fences, collaborate with coffee planters to redesign them to allow easy passage for elephants. Additionally, experimenting with temporary/seasonal fences, similar to those used in Sri Lanka (Fernando *et al.*, 2025), may be considered to protect seasonal crops such as maize and rice paddies, which are often on a smaller scale and managed by marginal farmers. This strategy would help prevent elephants from entering croplands while still allowing them to move through the landscape.

The conversion of National Highway 75 has restricted elephant movement and forced them to concentrate in a few villages, resulting in intense human-elephant conflicts. Thus, there is a pressing need to construct overpasses or underpasses at critical elephant crossing points along the highway. Our study indicates that effective, proactive management strategies, grounded in a thorough analysis of local conditions, can help safeguard elephants while minimising conflicts between humans and elephants.

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CONFLICT OF INTEREST

M. Ananda Kumar is a guest editor at the Journal of Wildlife Science for the special issue that includes this article. However, he did not participate in the peer review process of this article except as an author. The authors declare no other conflict of interest.

DATA AVAILABILITY

Data is available from the corresponding author on request.

AUTHOR CONTRIBUTIONS

Deepak Bhat contributed to data collection, project administration, data curation, mapping, and analysis.

Aditya Ghoshal has conceptualised, cleaned the data, wrote the manuscript, and performed data analysis.

Nisar Ahamad and Nandini NC have contributed to the field data collection and data compilation.

Ganesh Raghunathan has contributed to project administration and to the review and editing of the manuscript.

Ananda Kumar was involved in funding acquisition, conceptualisation of the idea, supervision, validation, methodology, project administration, writing the original draft, and review and editing.

DECLARATION OF THE USE OF GENERATIVE AI & AI-ASSISTED TECHNOLOGIES:

The author(s) used ChatGPT (ver: GPT 4.0) to help with R codes which are used in the data cleaning, GIS analysis, and mapping purposes. The author(s) thoroughly reviewed and edited the content generated and take(s) full responsibility for the content of the publication.

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Mortality investigations in wild Asiatic elephants (*Elephas maximus*) due to infected Kodo millet consumption in Bandhavgarh Tiger Reserve, Madhya Pradesh- A case study

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Abstract

In October 2024, a significant mortality event involving ten wild Asiatic elephants (*Elephas maximus*) occurred in the Bandhavgarh Tiger Reserve (BTR), Madhya Pradesh, India. This case study investigates the circumstances and causes underlying this incident, highlighting the emerging risks at the wildlife-agriculture interface. The affected elephants were part of a herd that had migrated from Chhattisgarh to BTR in recent years, demonstrating seasonal foraging behaviour in buffer zones and adjacent agricultural landscapes. Such interactions increase the chances of exposure to agricultural hazards, particularly during the periods of food scarcity.

Initial field assessments and post-mortem examinations conducted by a multidisciplinary team revealed no external trauma. However, generalised haemorrhages and significant gastrointestinal distension with undigested Kodo millet (*Paspalum scrobiculatum*) were evident. Histopathological analysis showed systemic vascular and epithelial damage, including pulmonary oedema, hepatic necrosis, and renal tubular degeneration, all suggestive of acute toxicosis. Chemical Residue Analysis was conducted to test for chemical residues in crops. Toxicological screening was negative for conventional poisons such as organophosphates, pyrethroids, heavy metals, and cyanide. Molecular testing for elephant endotheliotropic herpesvirus (EEHV), a potential differential diagnosis, also returned negative for all individuals. Cyclopiazonic acid (CPA), a mycotoxin produced by *Aspergillus* and *Penicillium* species, was detected at lethal concentrations in elephant tissue and gastrointestinal contents. Environmental and crop samples from nearby fields also revealed CPA infestation. Fungal cultures from elephant gut content and crop residues confirmed the presence of CPA-producing fungi.

The event underscores the risks posed by mycotoxin contaminations in millets grown under high-moisture conditions, particularly during unseasonal rainfall. The findings carry substantial implications for wildlife health, conservation policy, and agricultural practices in shared landscapes. Recommendations include restricting high-risk crop cultivation near protected areas, enhancing post-harvest storage practices, implementing routine mycotoxin surveillance, and promoting farmer awareness. This case also calls for coordinated action across forestry, veterinary, and agricultural departments under a "One Health" approach to prevent such incidents in the future.

Keywords: Cyclopiazonic acid (CPA), fungal poisoning, millets, mycotoxicosis, *Paspalum scrobiculatum*.

Introduction

Globally, wild Asiatic elephants are present in 13 range countries, and India holds the largest population of wild Asian elephants (*Elephas maximus indicus*) with an estimated population of 27,312 animals (MoEF&CC, 2017). Asiatic elephants are extremely sociable, forming groups of six to seven related females led by the oldest female, the matriarch. More than two-thirds of an elephant's day may be spent feeding on grasses, but it also eats large amounts of tree bark, roots, leaves, and small stems. Cultivated

crops such as bananas, rice, pulses and sugarcane are the most preferred foods (Sukumar, 1990). Human habitation is impinging on the boundary of many protected areas, and seasonal overabundance of food crops adjoining elephant habitats may also attract elephants irrespective of forage availability inside forests (Panda *et al.*, 2020).

State Forest Departments have implemented a range of site-specific and landscape-level interventions to prevent and mitigate human–elephant conflict across human-dominated landscapes. In Madhya Pradesh, these measures include the deployment of a mobile application (Gaj-Rakshak) for real-time tracking and alert dissemination of elephant movements in conflict-prone areas, GPS collaring of repeatedly conflict-involved elephants for continuous monitoring, and the installation of elephant-proof trenches and solar-powered fencing at strategic locations in and around Bandhavgarh and Sanjay–Dubri Tiger Reserves. Although many mitigation strategies are locally driven and provide short-term relief, several interventions have been effective in restricting elephant movement into human habitations and reducing conflict incidence.

The central Indian landscape, sprawling over 1,52,000 km² encompassing Madhya Pradesh, Maharashtra, and Chhattisgarh, is considered the heart of India's wildlife habitats. It is home to some of India's largest forest tracts, rich wildlife, as well as indigenous people who have been living in the forests since time immemorial. Historically, elephants were once abundant in Madhya Pradesh, but declined and disappeared by the early 20th century (Qureshi *et al.*, 2025). In 2018, a herd of 40 elephants dispersed from Chhattisgarh into eastern Madhya Pradesh (Natarajan *et al.* 2023). The herd initially entered through the Panpatha buffer range, exploring various parts of Bandhavgarh Tiger Reserve (BTR) before settling down. Forest Department closely monitored the elephants' movements and behaviour, through tracking teams. Since then, the elephant population in BTR has increased to 60 (by year 2023), including five solitary bulls. These elephants show seasonal movement patterns, with the Panpatha buffer range and BTR serving as key habitats at different times of the year. These recent range expansions have heightened human–elephant interactions, raising concerns for both residents and forest officials.

On October 29, 2024, staff at BTR in Madhya Pradesh discovered a distressing incident. Four elephants were found dead in the Sankhani and Bakeli areas of the Khotli range of BTR (23°45'20"N 80°55'28"E; Figure 1), while six others exhibited severe symptoms of illness. On October 30, four more elephants succumbed to death, followed by two additional fatalities on October 31, 2024. A total of 10 elephants died within two days.

Post-mortem findings consistently revealed large quantities of undigested Kodo millet in the stomachs of all 10 deceased elephants. Laboratory analyses revealed lesions in the heart, liver, kidney and spleen indicative of cardiac failure leading to passive venous congestion, hypoxia and resultant degenerative changes in the visceral organs. Additionally, the changes in the liver and kidney were indicative of acute toxicity. The toxicological analysis carried out on the samples were negative for common pesticides, heavy metals and hydrogen cyanide (HCN), but positive for cyclopiazonic acid (CPA). Details of the necropsies carried out, including laboratory (histopathological, haematology, and toxicology) examinations, are presented further in the result section of the article.

Elephants are known to be in negative interactions with humans causing “human–elephant conflict.” The most common forms of such conflict are crop-raiding (when elephants eat or destroy crops), property destruction, or simply people getting too close to elephants and triggering defensive behaviours that may lead to injury or death of people and elephants. Mortality of elephants due to Kodo millet consumption opens a new

dimension of human–elephant conflict, which needs proper understanding for its further implications on elephant conservation. The main objective of this paper is to highlight this novel challenging issue for scientists and wildlife managers, and equip them to handle similar cases in future holistically.

Study area

Bandhavgarh Tiger Reserve (23°30'–23°47' N, 80°47'–81°11' E) is located in the north-eastern part of Madhya Pradesh, the central India, along the northern slopes of the eastern Satpura range. It comprises two conservation units: Bandhavgarh National Park (448.8 km²) and Panpatha Wildlife Sanctuary (245.8 km²), with elevations ranging from 410 to 811 meters. The landscape includes rugged sandstone hills, densely forested valleys, and seasonal swamps. Bandhavgarh Hill, reaching 811 meters, lies at the reserve's centre. Numerous seasonal streams traverse the area, eventually joining the Son river. Vegetation types include moist peninsular low-level Sal forest, northern dry mixed deciduous forest, dry deciduous scrub, dry grassland, and west Gangetic moist mixed deciduous forest (Champion & Seth, 1968).

BTR supports a variety of herbivores such as chital (*Axis axis*), sambar (*Rusa unicolor*), gaur (*Bos gaurus*), wild pig (*Sus scrofa*), barking deer (*Muntiacus muntjak*), and nilgai (*Boselaphus tragocamelus*), Asian elephant, along with primates like langurs (*Semnopithecus entellus*), rhesus macaques (*Macaca mulatta*), etc.

The region experiences a tropical climate with three distinct seasons: summer (March–June), monsoon (July–October), and winter (November–February). Temperature ranges from 2.2°C to 46°C. Over 80% of the annual rainfall occurs during the southwest monsoon (Sonakiya, 1993), while occasional northeast monsoon showers contribute minor precipitation during winter (Prakasam, 2006). Agriculture in villages surrounding BTR primarily involves paddy, Kodo millet, Kutki (*Panicum sumatrense*), and maize in the Kharif season (June to October), and wheat, chickpeas, and mustard in the Rabi season (October to June).

The incident of elephant mortality on October 29, 2024 occurred near the Khitauli–Pataur core range boundary (23.75611° N, 80.9211° E), close to Salkhaniya revenue village (Figure 1). Preliminary observations revealed crop-raiding activity in Kodo millet fields the previous night, underscoring growing human–elephant conflict in the buffer zone (Figure 1).

Methodology for mortality investigations

On-site assessment

Upon notification of elephant mortality, a trained multi-disciplinary team comprising wildlife veterinarians, forest department officials, scientists from veterinary institutes, and wildlife biologists was mobilised to the site. The team conducted a preliminary assessment to secure the area and prevent human imprints. Further, GPS coordinates, ambient temperature, and weather conditions were also recorded (Figure 2).

Environmental cues suggestive of a possible cause of death, such as signs of poisoning or infectious diseases, were also recorded.

Post-mortem examination and sample collection

The post-mortem examination was conducted in accordance with standard guidelines for a systematic examination by the team of experts under the supervision of the Principal Chief Conservator of Forests (Wildlife), Madhya Pradesh. All the biological samples were collected and stored in properly labelled, leak-proof containers with waterproof tags (Figure 3). The biological samples were sent to the School of Wildlife

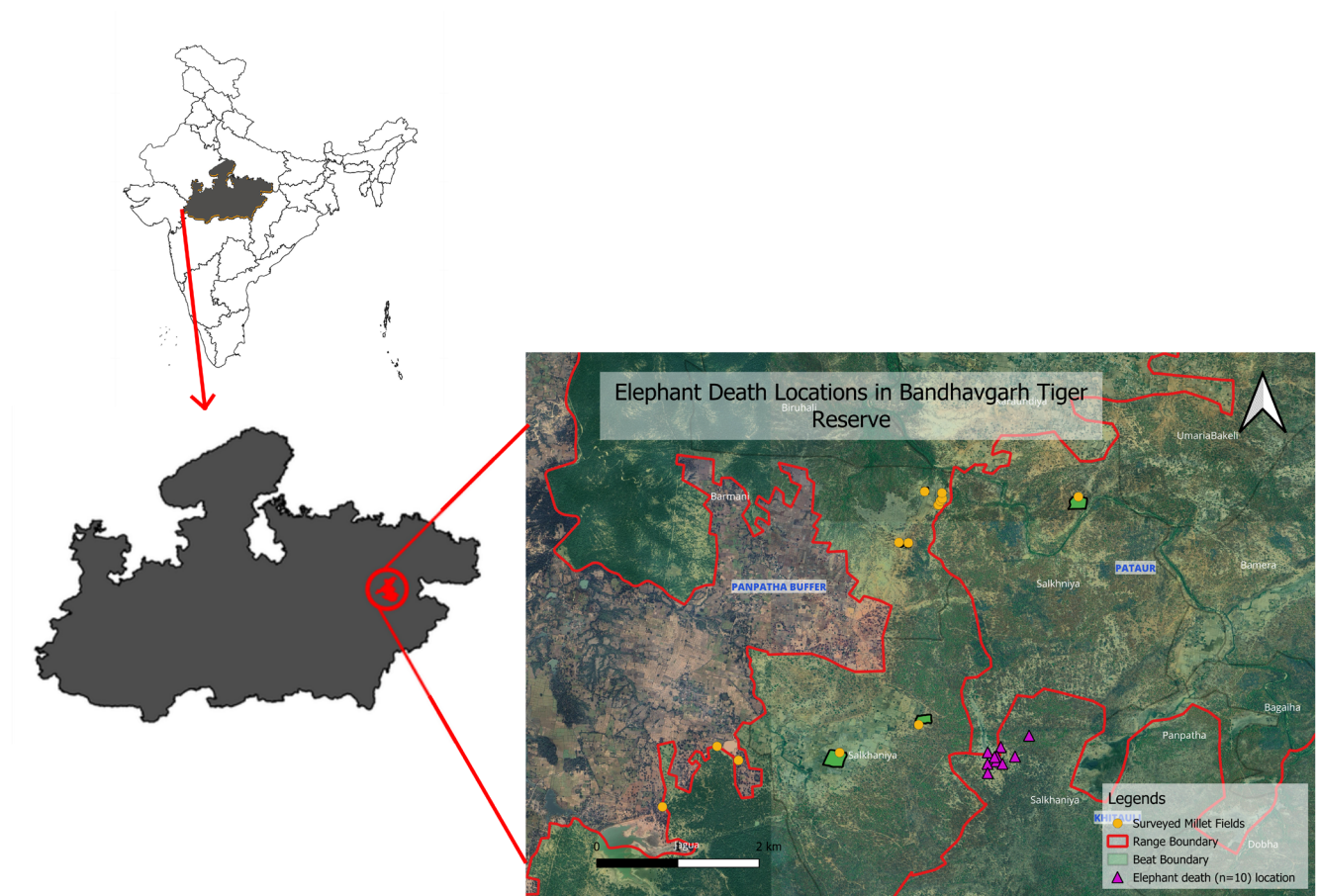


Figure1. Elephant mortality site at Bandhavgarh Tiger Reserve, M.P., India



Figure 2. Field samples and data collection exercise after the elephant mortality incident at Bandhavgarh Tiger Reserve, India.

Forensic and Health (SWFH), Nanaji Deshmukh Veterinary Science University, Jabalpur, Madhya Pradesh, ICAR-Indian Veterinary Research Institute (IVRI), Bareilly and State Forensic Science Laboratory, Sagar for histopathological and toxicological analyses and disease screening.

- **For histopathological examination**, tissue samples were collected from all the vital organs, including liver, kidney, heart, lungs, spleen, lymph nodes, stomach, intestines and tongue and fixed in 10% neutral buffered formalin and transported to the concerned laboratories.
- **For toxicological examination**, tissue samples of liver, kid-

ney, spleen, heart, lungs, as well as stomach contents and intestinal contents were collected in sterile containers and preserved in saturated salt solutions for further dispatch to the concerned laboratories.

- **For disease investigations**, tissue samples as well as swab samples were collected for PCR and culture and preserved in RNA-DNA protector and transported to the designated laboratories under cold chain conditions.
- **Environmental sampling**: Samples from standing crops and harvested crops of Kodo and paddy were collected and labelled. Water samples were collected from all the all-adjacent existing waterholes near to the actual incident



Figure 3. A female elephant, one out of 10 mortalities, died due to an infection of Kodo millet.

- spot. For the collection of water samples, the research team had also considered the latest elephant movement record compared to the old record. Samples from water bodies were also collected and labelled. Kodo millet samples were collected from the spot and also from the adjacent paddy fields. Other existing standing crops like corn, wheats were also collected for comparison. These samples were properly sealed and dispatched to the designated laboratories for toxicological investigations.

Documentation and reporting

All field and laboratory data were compiled in a standardized format, including post-mortem findings, chain-of-custody forms and laboratory findings. A comprehensive cause-of-death summary was prepared, integrating all diagnostic modalities, and shared with forest authorities for follow-up actions, including preventive management, surveillance, or legal proceedings.

Diagnostic investigations and results

Post-mortem examination and histopathological analysis

All ten elephants were subjected to post-mortem examinations, which revealed no external injuries or signs of trauma. There were generalised haemorrhages all over the mucosal layers and vital organs. Further, the gastrointestinal tracts were notably distended with ingesta, suggesting recent feeding. Internal organs exhibited signs of haemorrhage and congestion, prompting suspicion of acute toxicosis.

Tissue sections of vital organs revealed pulmonary oedema, extensive haemorrhages, emphysema in lungs, degenerated myocardial fibres and haemorrhages in heart, perivascular hepatocellular necrosis, fatty changes, vascular endothelial degeneration and haemorrhages in liver, acute tubular necrosis and haemorrhages in kidney, congested vessels with patchy haemorrhages in spleen, haemorrhages, epithelial sloughing, mild infiltration, necrotic mucosal changes in



Figure 4. Mycotoxigenic fungal infection in Kodo millet at the site.

gastrointestinal tract and extensive haemorrhage along the epithelial lining in tongue. These findings were generalised and similar in all ten cases. The lesions were consistent with acute toxicity, primarily affecting the vascular and epithelial integrity of major vital organs.

Toxicological analysis

Visceral organs, stomach and intestinal contents from all ten elephants were screened for toxins including hydrogen cyanide (HCN), nitrate-nitrite, heavy metals, organophosphate, organochlorine, carbamate, pyrethroid insecticides. The tests came back negative for all standard chemical and metallic toxins, ruling out anthropogenic chemical poisoning.

However, the gastrointestinal contents were observed to be positive for cyclopiazonic acid (CPA), a mycotoxin produced by fungi such as *Aspergillus* and *Penicillium* spp. The investigations detected CPA levels exceeding 100 ppb in elephant tissue samples. One elephant stomach content had 123,165 ppb CPA, approximately 10x higher than the reported LD₅₀ of 13,000 ppb (Nishie *et al.*, 1985).

These results collectively suggested acute mycotoxicosis due to CPA as the primary toxicological finding.

Disease investigation

Looking at the generalised haemorrhages all over the vital organs, tissue samples were also subjected to the detection of elephant endotheliotropic herpesvirus (EEHV), which is a fatal virus responsible for haemorrhagic disease and acute death in young elephants worldwide (Sree Lakshmi *et al.* 2023). However, all the samples tested negative for EEHV by terminase gene-based PCR.

Environmental and crop analysis

Crop sample analysis at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, through Liquid Chromatography–Mass Spectrometry (LC-MS) detected CPA in crop samples of Kodo millet. Environmental samples, including crop samples of Kodo millet and paddy, showed CPA concentrations ranging from 1,567 to 183,779 ppb. Further, the analyses found mycotoxigenic fungi infestation of the crop, caused by *Penicillium* spp., *Aspergillus* spp., *Fusarium* spp. and *Curvularia* spp. These fungi were cultured from Kodo millet, paddy, and elephant gut contents (Figure 4).

Overall diagnostic conclusion

The multidisciplinary diagnostic investigation conclusively identified cyclopiazonic acid (CPA) mycotoxicosis as the cause of death in all ten elephants. The presence of CPA-producing fungal species in Kodo millet consumed by the elephants, coupled with lethal levels of CPA in tissue and environmental samples, and characteristic histopathological lesions, confirmed acute mycotoxicosis and supported a diagnosis of fatal neurotoxicity caused by fungal infestation in consumed crops of Kodo millet (Table 1).

Discussion

The mass mortality event involving ten wild Asiatic elephants in BTR, Madhya Pradesh, in October 2024, represents one of the most significant toxicological wildlife mortality incidents in recent Indian conservation history. This tragedy underscores the pressing challenges posed by the increasing interface between wildlife and human-dominated landscapes, particularly in the context of climate change, crop infestation, and habitat fragmentation.

Ecological context and elephant behaviour

Recent range expansion of elephants into agrarian landscapes of central India due to dispersal from historically elephant-rich states like Odisha and Jharkhand has increased exposure to non-traditional risks, including contaminated crops. As elephants increasingly move into agrarian landscapes in search of food, conflict with human land use has become inevitable. The migration of a herd of elephants into BTR from Chhattisgarh in 2018 marked a pivotal ecological development. These elephants displayed strong seasonal movement patterns, frequently accessing buffer zones and revenue lands adjacent to protected areas, thereby heightening the risk of consuming contaminated crops.

The mortality event: clinical and field observations

The October 2024 incident of 10 elephant deaths killed nearly 25% of the local elephant population. It occurred in proximity to agricultural fields where Kodo millet had recently been harvested or was still standing. The absence of external injuries and the presence of gastrointestinal distension filled with millet pointed toward a non-traumatic, non-infectious, and possibly toxic aetiology. The rapid progression of symptoms and death in otherwise healthy elephants was consistent with acute poisoning.

Histopathological evidence of acute toxicosis

Histopathological examinations across all 10 elephants revealed a strikingly consistent pattern of lesions, including multi-organ dysfunction. These lesions indicated systemic vascular and cellular damage and supported a diagnosis of acute toxicity affecting multiple organ systems (Larkin *et al.* 2020; Saganuwan *et al.* 2023).

Toxicological analysis and confirmation of CPA

The core of the diagnostic investigation was toxicological screening, which revealed the presence of cyclopiazonic acid (CPA), a secondary metabolite produced primarily by *Aspergillus flavus* and *Penicillium cyclopium*. CPA was detected in pooled tissue samples at concentrations exceeding 100 ppb. Critically,

gastrointestinal contents from the deceased elephants, as well as crop and environmental samples, contained CPA at extremely high levels.

Culture-based assays and morphology confirmed the presence of mycotoxigenic fungal species such as *Aspergillus*, *Penicillium*, *Fusarium*, and *Curvularia*, which are well-known producers of CPA, aflatoxins, and other harmful metabolites. These results were corroborated by fungal cultures from both the Kodo millet samples and the gut contents of affected elephants.

Although there is limited species-specific data, elephants are expected to be susceptible to mycotoxins affecting the liver and nervous systems due to their slow metabolism and large body mass. Exposure to aflatoxins and fumonisins could lead to significant liver toxicity and neurologic symptoms, similar to effects seen in other large mammals such as horses (Ref.). One of the possible causes of no death record of other wild and domestic herbivores consuming fungal-infected Kodo might be due to ruminants having four chambers, whereas elephants possess a monogastric digestive system.

Mycotoxins and their impact on wildlife

Mycotoxins are secondary metabolites produced by fungi (Reddy *et al.*, 2010), especially in moulds of *Aspergillus*, *Fusarium*, and *Penicillium* species that pose serious health risks to animals and humans when ingested. These toxins contaminate agricultural products under favourable environmental conditions, particularly high moisture and temperature, leading to animal health and significant economic losses (Hassan *et al.*, 2001).

CPA is a potent mycotoxin with known hepatotoxic, nephrotoxic, and neurotoxic properties. It inhibits calcium-dependent ATPase in the endoplasmic reticulum, leading to cellular apoptosis and necrosis, particularly in liver and kidney tissues (Bhanu, 2024). Although much of the existing toxicological data is based on livestock models such as poultry and swine, extrapolation to megaherbivores such as elephants is supported by their known sensitivity to hepatotoxic agents due to their slow metabolic rate and large gut fermentation systems (Greene *et al.* 2019).

The resistance of mycotoxins to degradation, even under high temperatures or post-harvest processing, makes them insidious threats to both humans and animals (Khan *et al.*, 2024). The lethal concentration of CPA in the sampled elephant stomach content firmly establishes this compound as the proximate cause of death.

Historical precedent of Kodo poisoning in elephants and implications for human safety

This is not the first documented case of elephant mortality due to mycotoxins. A similar incident was also reported in December 1933, when 14 elephants were suspected to have ingested Kodo millet and subsequently found dead near the Vannathiparai Reserve Forest in Tamil Nadu, close to the Kerala border (Morris, 1934).

Kodo millet has beneficial properties for human health, and the government of India is promoting millets in the central Indian landscape, where precipitation is low. However, there were reports of 'Kodo poisoning', especially from Uttar Pradesh and Madhya Pradesh (Deepika *et al.* 2022). Bhide (1962) and Bhide & Aimen (1959) noted that the husk and foliage of Kodo millet frequently acquire toxic properties, a phenomenon that is frequently associated with heavy rainfall. In the states of Madhya Pradesh and Chhattisgarh, this form of poisoning is locally known as Malona, underscoring long-standing indigenous knowledge of this hazard. Rao & Husain (1985) were the first to establish the connection between the mycotoxin cyclopiazonic acid (CPA) and Kodo millet seeds, which causes "kodua poisoning."

Table 1. Summary of Diagnostic Investigations and Findings in Elephant Mortality at Bandhavgarh Tiger Reserve, Madhya Pradesh

Investigation Type	Samples Tested	Methodology	Findings	Interpretation
Post-mortem Examination	Ten elephants (Complete necropsy)	Gross examination as per standard wildlife necropsy protocols	No external injuries. Distended gastrointestinal tract. Internal congestion and haemorrhages in lungs, liver, heart, kidneys, and GI tract	Suggestive of acute systemic toxicosis
Histopathology (IVRI, Bareilly and SWFH, Jabalpur)	Lungs, heart, liver, spleen, kidneys, stomach, intestine, tongue (n = 10 elephants)	Tissue processing, H&E staining, light microscopy	Pulmonary oedema, haemorrhages, hepatic necrosis, tubular necrosis in kidneys, myocardial degeneration, GI epithelial sloughing	Consistent with acute toxicity; generalised vascular and cellular damage
Toxicology – (IVRI, Bareilly)	Visceral organs, stomach and intestinal contents (n = 10)	Pooled sample screening for toxins (AAS, GC-MS, colorimetric tests)	Negative for HCN, nitrate-nitrite, heavy metals, organophosphates, organochlorines, pyrethroids, and carbamates. Positive for Cyclopiasonic acid (CPA) >100 ppb in pooled samples	Indicative of CPA mycotoxicosis as the primary toxicant
Toxicology – (ICRISAT, Hyderabad)	Kodo millet, paddy, vomitus, elephant stomach contents (n = 23)	LC-MS and ELISA	CPA levels ranging from 1,567 to 183,779 ppb; CPA in elephant stomach content: 123,165 ppb. Aflatoxins within safe limits	CPA levels well above known LD ₅₀ (13,000 ppb). Confirms ingestion of highly contaminated millet
Fungal Culture (SWFH, Jabalpur and JNKVV, Jabalpur)	Crop samples, elephant gut content	Microscopic examination post incubation	Presence of <i>Penicillium</i> , <i>Aspergillus</i> , <i>Fusarium</i> , and <i>Curvularia</i> spp.	Fungal species known to produce CPA. Supports toxicological findings
Molecular Diagnostics (EEHV PCR) (SWFH, Jabalpur)	Blood, oral/nasal/rectal/conjunctival swabs, internal organs (n = 10 elephants)	Terminase gene-based PCR	All samples negative for EEHV	Excludes EEHV as a cause of mortality
Environmental Analysis (SFSL, Sagar and IVRI, Bareilly)	Water, soil, dung, crop residue	Chemical screening for toxins	No chemical/toxic pesticide infested found.	Rules out agro-chemical poisoning.

It is important to clarify that consumption of Kodo millet per se is not inherently fatal. The risk arises when the grain is contaminated with toxigenic fungi such as *Penicillium* spp. or *Aspergillus* spp., which are capable of producing CPA, which is an indole-tetramic acid mycotoxin that inhibits sarcoplasmic/endoplasmic reticulum Ca²⁺-ATPase, leading to disruption of calcium homeostasis, hepatocellular damage, and neuromuscular dysfunction (Seidler *et al.*, 1989).

Comparative host susceptibility plays a key role in the outcome of CPA exposure. Large herbivores, such as elephants, are highly vulnerable due to their bulk consumption of contaminated feed and limited detoxification capacity. Conversely, humans are comparatively less susceptible, as fungal infestations can be minimised by traditional practices such as sun-drying or mechanical cleaning, which significantly reduce mycotoxin loads. Thus, it is important to understand that while Kodo millet remains a safe dietary staple for humans when properly processed, its fungal colonisation and subsequent CPA production represent a critical risk factor for wildlife health in contaminated landscapes.

Contributing factors: climate, agriculture, and conservation conflict

This tragic mortality event is symptomatic of broader ecological and anthropogenic trends. Climate variability, particularly unseasonal rainfall during harvest periods, creates moist conditions conducive to fungal colonisation of standing crops

(Zingales *et al.* 2022). Coupled with improper post-harvest storage, these environmental changes have led to increasing incidences of mycotoxin infestations.

Elephants, driven into farmlands due to habitat shrinkage and food shortages, are at risk of ingesting contaminated crops, especially in buffer zones and village margins adjacent to protected areas. The revenue village of Salkhaniya, less than a kilometre from BTR's boundary, was cultivating Kodo millet during the incident period, and preliminary field reports confirmed crop-raiding activity by elephants the night before the mortality event.

The lack of buffer policies restricting high-risk crops near protected areas, the absence of routine crop testing, and limited farmer awareness about fungal infestation collectively represent critical gaps in the landscape-level management of wildlife-agriculture interactions.

Legal and institutional dimensions

The incident prompted judicial scrutiny under the National Green Tribunal (NGT), Central Zone Bench, Bhopal, which linked the deaths to CPA mycotoxicosis exacerbated by climate-driven fungal infestation. The Tribunal acknowledged that these deaths occurred despite the declaration of BTR and its buffer zones as an Eco-Sensitive Zone in 2016 under the Environment Protection Act, 1986. The incident serves as a legal precedent for integrating environmental, agricultural, and wildlife safety

concerns under one regulatory umbrella. Detailed guidelines have already been proposed by the NGT, Central Zone Bench, Bhopal, under point number 34 (<https://indiankanoon.org/doc/46470666/>).

Management and policy implications

A multi-pronged strategy is essential to prevent recurrence of such incidents. It was also mentioned by NGT that the incident took place in the eco-sensitive zone, hence their directive includes:

- **Ecological zoning and buffer management:** Restricting the cultivation of known mycotoxin-prone crops such as Kodo millet and paddy within a buffer radius of protected areas.
- **Farmer sensitization and incentivization:** Awareness programs and subsidies for growing safer alternative crops (*e.g.*, legumes) in conflict-prone zones.
- **Crop surveillance and mycotoxin screening:** Establishment of field-based testing laboratories to regularly monitor aflatoxins and CPA levels in crops grown near wildlife habitats.
- **Post-harvest management:** Introduction of improved storage techniques, moisture control, and fungal inhibition strategies, including bio-control agents and hermetic storage systems.
- **Climate-responsive agricultural policies:** Development of fungal forecasting models using meteorological data to guide sowing, harvesting, and drying schedules.
- **Veterinary preparedness:** Strengthening wildlife health infrastructure to enable real-time disease investigation and sample analysis.
- **Landscape-level wildlife corridors:** Ensuring undisturbed migratory routes for elephants to reduce reliance on human-dominated fields for foraging.
- **Interdepartmental coordination:** Forest, agriculture, and veterinary departments must collaborate under an integrated “One Health” framework addressing zoonotic, environmental, and ecological intersections, recognising that human, animal, and environmental health are deeply interconnected.

Conclusion

The BTR elephant mortality event is a serious reminder of the ecological fragility at the wildlife-agriculture interface. The confirmed role of CPA, —a fungal mycotoxin,— in this mass mortality highlights the urgent need to recognise and mitigate non-traditional toxic threats to wildlife. As climate change alters fungal growth patterns and increases the likelihood of mycotoxin infestation, policy and management approaches must evolve from reactive to anticipatory. In such scenarios, as per the NGT guidelines, there should be continuous crop surveillance in eco-sensitive zones, especially during the harvesting season, along with community awareness and sensitisation (<https://indiankanoon.org/doc/46470666/>).

Protecting elephants, keystone species of immense ecological and cultural importance, requires not only preserving forest cover but also managing the agrarian matrix they traverse. A comprehensive, evidence-based response that integrates science, policy, and community participation will be pivotal in ensuring the coexistence of wildlife and human livelihoods in shared landscapes.

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CONFLICT OF INTEREST

Dr Parag Nigam is an academic editor at the Journal of Wildlife Science. However, he did not participate in the peer review process of this article except as an author. The authors declare no other conflict of interest.

DATA AVAILABILITY

Data and reports of laboratory analyses are available from the corresponding author on request.

AUTHOR CONTRIBUTIONS

AVK, SS, LK, DAK, SA, VPK, SR Contributed in entire management and resource availability during rescue operation and also provided inputs on the draft; SJ, NR, HS, KM SS analysed the different samples; TK contributed in sample and data collection. AM, NR, TK prepared first draft; RS, AM, NR, TK edited and refined the manuscript; PN, PRK provided inputs on the draft; NG collected the samples and performed postmortems.

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Millet, Mycotoxins, and Megafauna: The Bandhavgarh Elephant Tragedy

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Abstract

The Asian elephant (*Elephas maximus*) has experienced severe population decline across its range due to poaching, habitat loss, fragmentation, and escalating human–elephant conflict (HEC). In Central India, HEC has intensified over the past two decades as elephants expand westward into increasingly fragmented landscapes dominated by smallholder agriculture. In this context, the tragic death of ten elephants near Bandhavgarh Tiger Reserve in October 2024 highlights an emerging and underappreciated conservation risk linked to agricultural mycotoxins. Clinical investigations established kodo millet (*Paspalum scrobiculatum*) poisoning, implicating cyclopiazonic acid (CPA), a fungal mycotoxin produced by *Aspergillus* species, as the cause of mortality. This study examines the Bandhavgarh incident to understand its ecological, agronomic, and conservation implications. We situate kodo millet within its historical and contemporary agronomic context, emphasizing its prevalence in marginal, rain-fed landscapes adjoining elephant habitats, where crop-raiding is frequent. We review the long-standing documentation of kodo millet toxicity in humans, its association with fungal contamination during wet-harvest conditions, and its relevance to wildlife health. We argue that small, fragmented elephant populations in Central India are particularly vulnerable to such episodic risks. We further discuss, how increasingly erratic monsoons and heavy rainfall events, may elevate fungal proliferation and mycotoxin exposure in staple crops. To mitigate these risks, we outline integrated management strategies encompassing biological control agents, weather-based disease forecasting, field surveillance, and improved post-harvest drying and storage. We also acknowledge scientific and operational constraints in deploying biological controls, including environmental variability, strain persistence, and formulation stability. We emphasize that safeguarding elephants in Central India requires an integrated approach linking agricultural safety, landscape connectivity, and HEC management. Strengthening corridors, improving crop management, and embedding wildlife health into land-use planning are essential to prevent similar tragedies and promote long-term coexistence between people and elephants in a rapidly changing landscape.

Keywords: Central India, cyclopiazonic acid, elephant, kodo, millet.

The decline of the Asian elephant (*Elephas maximus*) is primarily driven by poaching, habitat loss, fragmentation, and other anthropogenic activities (Leimgruber *et al.*, 2003; Chen *et al.*, 2022; Pandey *et al.*, 2024a). These factors have significantly reduced their population and habitat across Asia (Shaffer *et al.*, 2019; de Silva *et al.*, 2020). The species has garnered global concern due to a nearly 50% decline in their population over the past three generations (Williams *et al.*, 2020). Over 60% of suitable elephant habitat has been lost since the 1700s, with significant fragmentation reducing the average patch size by over 80% (de Silva *et al.*, 2020). Human population growth has historically contributed to the range contraction of Asian elephants and limited their habitat (Liu *et al.*, 2017). This loss is largely due to agricultural expansion, urbanization, and infrastructure development, which have isolated elephant populations and reduced their genetic diversity (Chen *et al.*, 2022; Neupane *et al.*, 2020; Leimgruber *et al.*, 2003). These factors also lead to habitat deterioration, increased human–elephant conflict, and direct threats like poaching (Joshi *et al.* 2009; He *et al.* 2020). Small, isolated populations exhibit low genetic diversity and high inbreeding, which threaten their long-term viability (He *et al.*, 2020; Chen *et al.*, 2022). Particularly in areas outside Protected Areas (PAs), especially along their borders, habitat degradation exacerbated by human–elephant conflicts (HEC) poses a major threat to the species' survival (Gubbi, 2012; Tilman *et al.*, 2017). Over the past decade, Human–Elephant Conflict (HEC) has intensified across many Asian countries, resulting in significant economic losses and fatalities of both people and elephants (Gubbi, 2012; Shaffer *et al.*, 2019). As human activities

continue to expand into elephant habitats, mitigating HEC has become essential for ensuring the long-term survival of elephant populations in their natural ranges (Shaffer *et al.*, 2019).

In the last two decades, HEC in the Central Indian landscape has spiked (Tripathy *et al.*, 2021; Natarajan *et al.*, 2024; Habib *et al.* 2025). The central Indian elephant range extends over 21,000 sq.km in the states of Odisha, Jharkhand, Chattisgarh, southern West Bengal, and the eastern part of Madhya Pradesh (Singrauli and Anuppur District). Chhattisgarh has a small elephant population that had migrated from Jharkhand and Odisha during the 1980-90s. Historically, elephants were found in parts of northern Chhattisgarh and Madhya Pradesh, but by the early 20th century, they were considered locally extinct in Madhya Pradesh (Natarajan *et al.*, 2023). Due to various anthropogenic pressures, elephants are forced to move towards further west (Areeparampil, 1996; Kumar *et al.*, 2023). In 2018, a herd of 40 elephants from Chhattisgarh moved to Madhya Pradesh (Uikey *et al.*, 2024; Natarajan *et al.*, 2023). The herd initially entered through the Panpatha buffer range, exploring various parts of Bandhavgarh Tiger Reserve before settling down. Forest department closely monitored this process, forming tracking teams to observe and manage the elephants' movements and behaviour (Uikey *et al.*, 2024). Since then, the elephant population in Bandhavgarh had increased to 60 by 2023, including five solitary bulls. These elephants showed seasonal movement patterns, with the Panpatha buffer range and Bandhavgarh Tiger Reserve serving as key habitats at different times of the year. On October 29, 2024, ten elephants were found dead within the territorial limits of Salkhaniya Revenue Village, located 1 km from the boundary of Bandhavgarh Tiger Reserve (Ambade *et al.*, 2025). Kodo millet (*Paspalum scrobiculatum*) poisoning in this case is clinically established (Ambade *et al.*, 2025). In this article, we discuss the incident with a focus on strengthening local HEC management, promoting safer crop cultivation practices, and highlighting its broader implications for elephant conservation in the Central Indian landscape. Given that the Bandhavgarh incident involved a cultivated crop rather than natural forage, it is important to understand the ecological, agronomical, and historical context of kodo millet in India. Kodo is widely grown in marginal, rain-fed landscapes adjoining forested areas, where elephants frequently forage, making it a key interface crop in human–elephant interactions.

Kodo Millet: Resilient Ancient Grain with Nutritional and Agronomic Value

Kodo millet is native to India and belongs to the genus *Paspalum* (subfamily *Panicoideae*), which includes over 400 species distributed across the hot tropical and subtropical regions of the Old World (de Wet *et al.*, 1983). It is one of the most resilient small millets, capable of growing in marginal, low-fertility soils and areas with chronic moisture deficits. The crop requires 110–130 days to mature, which is longer than most other small millets. It is cultivated in parts of West Africa, Southeast Asia, Pakistan, and India (Galinato *et al.*, 1999). Globally, kodo millet is known by several names, including kodohirse, creeping paspalum, ditch millet, and Indian *Paspalum* (Knees & Gupta, 2013; Hariprasanna, 2017). Within India, it is locally called *arika* (Telugu), *varagu* (Tamil and Malayalam), *harka* (Kannada), *kodra* (Gujarati, Marathi, Punjabi), *kodua* (Odia), and *kodo* (Hindi and Bengali) (Deepika *et al.*, 2022).

Archaeological evidence suggests that kodo millet has been cultivated in India since Neolithic times, with remains recovered from sites such as Nevasa, Hallur, and Nagra (Kajale, 1974). Its cultivation as an annual crop has been documented for over 3,000 years in southern Rajasthan and parts of Maharashtra (de Wet *et al.*, 1983). India remains the world's largest producer

of kodo millet, contributing approximately 0.08 million tonnes from about 0.2 million hectares (Bhat *et al.*, 2018). The crop is predominantly grown on marginal lands, often in sloping or undulating terrains within tribal regions (Yadava & Jain, 2006). Nutritionally, kodo millet is rich in carbohydrates and proteins comparable to wheat and rice (Deepika *et al.*, 2022). It also contains essential minerals such as sodium, calcium, iron, potassium, magnesium, and zinc (Longvah *et al.*, 2017), along with B vitamins and high phenolic content (Hegde *et al.*, 1989).

Kodo Millet Poisoning: Mycotoxin Risks and Historical Perspectives

Despite the nutritional advantages of kodo millet, for which the government of India is promoting its adoption across Central India's arid regions, 'kodo poisoning' cases have been documented in Madhya Pradesh and Uttar Pradesh (Deepika *et al.*, 2022). The scientific documentation of kodo millet poisoning dates back to the late 18th century. Chevers (1870) documented that consuming kodo millet grains can result in adverse health effects, particularly when the grains mature and are harvested during rainy days. Similarly, the *Indian Medical Gazette* (1922) detailed an incident of acute "kodon" poisoning reported by an assistant surgeon in Shahjahanpur district, Uttar Pradesh (Deepika *et al.*, 2022). The report described four individuals who consumed bread made from kodo millet flour and subsequently experienced symptoms such as vomiting, dizziness, and unconsciousness shortly after their meal (Swarup, 1922). However, there was also a historical report of kodo poisoning cited in Bhat (1983): "The problem of mycotoxins in kodo millet was well recognized in the ancient Indian as well. A text entitled "*Arthashastra*" (economics) written in the year 300 B.C. by Chanakya refers to the killing of tigers by baiting them with the Kodo millet."

Bhide (1962) and Bhide & Aimen (1959) noted that the husk and foliage of kodo millet frequently acquire toxic properties, a phenomenon that is frequently associated with heavy rainfall. In the states of Madhya Pradesh and Chhattisgarh, this form of poisoning is locally known as "Matawna Kodoo" or "Matona Kodo" (Pall *et al.*, 1980; Ansari & Shrivastava, 1991). This seasonal association has fostered a belief among farmers in certain regions that kodo millet becomes toxic following rainfall. Rao & Husain (1985) were the first to establish the connection between the mycotoxin cyclopiazonic acid (CPA) and kodo millet seeds, which causes "kodua poisoning." They determined that the seeds were infected with *Aspergillus flavus* and *Aspergillus tamarii*, both of which produce cyclopiazonic acid. This was the initial documented association between kodua poisoning and a mycotoxin (Rao & Husain, 1985). Cyclopiazonic acid (CPA) is a potent mycotoxin that can cause a range of health problems, including gastrointestinal distress, liver damage, and neurological disorders (Ostry *et al.*, 2018). In severe cases, it can lead to death. Biologically, CPA is a specific inhibitor of sarco (endo) plasmic reticulum Ca²⁺-ATPase (Ostry *et al.* 2018). While humans have been aware of the risks associated with consuming contaminated kodo millet for centuries, the impact of this toxic grain on wildlife was sporadic in the 19th and 20th centuries.

Kodo Millet Toxicity, Central India's Elephant Population

As depicted in ancient literature from the Kurinji landscape, Asian Elephants have been raiding crops since historic times (for details see Oommen, 2019). There are texts which describe elephants roaming in millet-rich hills, and often mountain dweller guarding their fields using a platform. There is information in the poetry about bull elephants often raiding millet fields (Oommen, 2019). These historical depictions highlight the persistent conflict between elephants and humans over millet.

A similar incident was also reported in December 1933, 14 elephants were suspected to have ingested kodo millet and subsequently found dead near the Vannathiparai Reserve Forest in Tamil Nadu, close to the Kerala border (Morris, 1934).

Historical records and writings from the Mughal emperors of the 16th and 17th centuries (Sukumar, 2003) provide evidence that elephants were once broadly distributed across central India, from southern Uttar Pradesh through Madhya Pradesh to Chhattisgarh. Although they eventually disappeared from these areas, they have now first recolonized Chhattisgarh, and then Madhya Pradesh. In central India, the elephant population is small, isolated groups within a highly fragmented landscape, and is still venturing into new areas. As a result, the likelihood of elephants raiding kodo millet in this area is significantly higher. The relatively low number of elephants in this landscape can be attributed to factors such as historic mass capture, poaching, habitat fragmentation and loss, and human-elephant conflict. However, the impact of elephant deaths caused by kodo poisoning on the region's small and fragmented elephant populations cannot be entirely overlooked, and several such incidents may have gone unnoticed.

Furthermore, Central India has experienced significant shifts in its precipitation patterns (Mukharjee *et al.*, 2018), characterized by an increase in the frequency of heavy rainfall events and a more erratic monsoon season. Studies have shown a rise in localized heavy rainfall occurrences, while the timing and intensity of the monsoon have become less predictable, leading to both droughts and floods in different parts of the region (Kishore *et al.*, 2016; Sørland & Sorteberg, 2016). Climate change is expected to impact food security through both direct effects on crop yields and indirect effects on food safety, as acknowledged by the FAO (2008). However, the majority of research on climate change and food security is primarily concentrated on yields, with limited attention given to food safety. There is a pressing need for quantitative assessments of the projected impacts of climate change on food safety, particularly concerning mycotoxin contamination in cereals and other crops.

Mitigation Measures-Mycotoxin Contamination

The primary states producing kodo millet in India: Madhya Pradesh, Uttar Pradesh, Maharashtra, Chhattisgarh, Tamil Nadu, and Karnataka, are all home to the Asian elephant (consisting of ~34% of the elephant population). Crop raiding is one of the major causes of human elephant conflict in the central Indian landscape (Natarajan *et al.*, 2024). Hence, we have discussed the strategies for mitigating mycotoxin contamination in details here.

Biological control agents (BCAs) such as *Trichoderma spp.* and *Bacillus subtilis* are effective in inhibiting the growth of toxigenic fungi by colonizing plant surfaces and producing antifungal metabolites. This approach reduces the need for chemical fungicides and offers a more sustainable pathway for managing fungal contamination. Several BCAs have demonstrated potential in suppressing toxigenic fungi and reducing mycotoxin production. Yeasts such as *Saccharomyces cerevisiae* can inhibit *Aspergillus flavus* through the production of volatile organic compounds (VOCs) and binding mechanisms that remove mycotoxins from contaminated environments (Hassan *et al.*, 2021; Oufensou *et al.*, 2023; Alasmar *et al.*, 2020). Similarly, *Bacillus megaterium* and *Bacillus subtilis* can suppress fungal growth and mycotoxin synthesis, including aflatoxins and ochratoxins, through the release of inhibitory VOCs (Saleh *et al.*, 2021; Zohri *et al.*, 2018). Other bacterial strains, such as *Lactococcus lactis* and *Pseudomonas fluorescens* have also shown strong antifungal activity in laboratory studies (Zohri *et al.*, 2018). Additionally, non-toxigenic strains of *Aspergillus niger* and *A. tubingensis* have been used to competitively exclude toxigenic fungi, resulting in reduced mycotoxin levels (Aukkasarakul *et al.*, 2014).

Overall, BCAs provide an environmentally friendly alternative to synthetic fungicides by minimizing chemical inputs, lowering the risk of fungicide resistance, and promoting natural antagonistic interactions in agroecosystems (Hassan *et al.*, 2021; Oufensou *et al.*, 2023; Ren *et al.*, 2020; de la Huerta-Bengoechea *et al.*, 2022). Their adoption could be facilitated through agricultural cooperatives, farmer training programs, and field demonstrations to validate performance under real-world conditions.

However, the effectiveness of BCAs can vary across environmental gradients, particularly with changes in temperature, humidity, rainfall patterns, and soil microbial communities, which may influence their establishment and persistence in the field. The durability of introduced strains over an entire cropping season also remains uncertain in rain-fed, low-input systems where conditions are highly variable. Furthermore, the economic feasibility of repeated BCA applications and formulation stability under tropical field conditions requires further evaluation. Addressing these challenges will require region-specific field validation trials, development of locally adapted strains, and integration of BCAs within broader crop and post-harvest management strategies rather than relying on them as a stand-alone solution.

Furthermore, timely taken action, guided by predictive weather models, can effectively prevent fungal diseases and reduce mycotoxin contamination. Real-time weather-based alerts via communication tools or mobile apps can help farmers target critical infection periods, minimizing costs and environmental impact. Ensuring access to safe fungicides through cooperatives and extension services is essential for widespread adoption. Continuous monitoring of fields during crop growth is essential for the early detection of fungal infections. Early intervention can prevent the spread of infection and reduce mycotoxin production. The government can establish a network of trained field scouts equipped with diagnostic kits and mobile devices to carry out regular field inspections. By providing real-time updates and advice to farmers, these scouts can play a vital role in early detection and timely management of fungal diseases.

Post-harvest handling and storage are crucial to reducing mycotoxin contamination, which thrives in moist and poorly managed conditions. Rapid drying of crops using subsidized solar or biomass dryers, centralized drying facilities, and proper training can prevent fungal growth. Safe storage practices, such as using hermetically sealed bags, metallic silos, or climate-controlled community warehouses, are essential to protect dried crops. Financial incentives can support farmers in adopting modern storage solutions. Regular monitoring for mycotoxins through mobile testing labs and certification programs ensures food safety and better market prices for toxin-free produce. Additionally, promoting good handling and sorting practices, such as using improved threshing tools and manually removing damaged grains, helps minimize fungal entry. Awareness campaigns and training can further enhance the adoption of these practices, ensuring safer and higher-quality crops. Simultaneously, studying elephant movement in the central Indian landscape is vital, given the region's highly fragmented habitats and the frequent crop-raiding behaviour.

Conclusion

The tragic mortality of ten elephants in Bandhavgarh Tiger Reserve underscores the emerging risks associated with mycotoxins, specifically cyclopiazonic acid (CPA). The incident in Bandhavgarh stresses the urgent need for a multi-sectoral approach to mycotoxin management, especially in areas where wildlife and agriculture intersect. This incident serves as a wake-up call to the interconnectedness of agriculture, wildlife health, and environmental change, highlighting the need for more comprehensive monitoring and mitigation strategies. In the coming years, climate change may increase the prevalence of fungal infestations in crops like kodo millet, creating new threats

for both wildlife and humans. In light of this, it is imperative to improve crop storage methods, enhance early detection of mycotoxins in food supplies, and raise awareness among local farming communities regarding safe agricultural practices.

Additionally, capacity-building initiatives should be conducted for local farmers, agricultural departments, forest officials, and other relevant agencies to address fungal infestations in agricultural crops and implement effective mitigation measures. Moreover, efforts to reduce HEC, such as strengthening elephant corridor connectivity and ensuring sustainable forage availability within protected areas (Pandey et al., 2024 a, b), are critical for safeguarding elephant populations in Central India. The integration of environmental, land-use planning, agricultural, and wildlife health measures will be the key in preventing similar incidents, fostering coexistence, and ensuring the long-term survival of elephant populations in the central Indian landscape. This incident highlights the need for a holistic approach to conservation that takes into account the complexities of ecosystem health, human-wildlife interaction, and agricultural sustainability.

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CONFLICT OF INTEREST

Parag Nigam & Bilal Habib hold academic editor positions at the Journal of Wildlife Science. However, they did not participate in the peer review process of this article except as an author. The authors declare no other conflict of interest.

DATA AVAILABILITY

Data is available from the corresponding author on request.

AUTHOR CONTRIBUTIONS

A.N. wrote the first draft of the manuscript. R.K.P., P.N. & B.H. provided critical intellectual inputs, revised the manuscript for important content, and approved the final submission.

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