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Quantifying elephant mortality in a changing landscape: insights from Jharkhand, India

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Elephant mortality in Jharkhand has reached critical levels, primarily driven by anthropogenic pressures and habitat degradation, which has intensified their movement into human-dominated landscapes. We conducted a comprehensive analysis of elephant mortality trends in Jharkhand, India, spanning from 2000 to 2023. This study investigates the influence of habitat alterations, anthropogenic activities, and other ecogeographical factors on the escalating elephant mortality in the region. In the last 23 years, forest cover has changed up to 6% and subsequently, built-up areas have risen by 39.34%, further encroaching on elephant habitats and corridors. During the period a total of 225 elephant deaths were reported, with 152 of these caused by various anthropogenic activities and highest death was reported due to electrocution (n=67). The highest number of elephant deaths (anthropogenic) occurred during the monsoon season, with Ranchi division reporting the most mortalities, followed by East Singhbhum and Saraikela. At the village level, the analysis revealed that areas characterized by higher road densities and reduced forest cover experienced high elephant mortalities. This pattern suggests that increased infrastructure development and habitat degradation may be contributing to the escalation of human-elephant conflicts in these regions. These findings underscore the urgent need for conservation actions, including reforestation, establishment of protected corridors, improved infrastructure planning, and awareness generation at the local level to reduce elephant mortalities and overall human elephant conflict in Jharkhand.

KEYWORDS
elephant mortality, electrocution, fragmentation, Jharkhand, LULC, Ranchi

1 Introduction

A critical conservation issue that has broad ramifications for both the preservation of wildlife and human livelihoods is the growing human-elephant conflict (HEC) in India. Asian elephants have historically wandered freely among habitats in India's vast and interconnected forested landscapes (Sukumar, 2003). These landscapes have been severely disrupted, nevertheless, by post-colonial land-use changes, infrastructural development, and agricultural intensification (Roy, 2023). Elephant habitats have shrunk to smaller, isolated areas that are frequently surrounded by human settlements as a result of human populations increasing in tandem with agriculture (Choudhury, 1999). Elephant's access to natural resources has been restricted by their confinement, which has forced them to seek food and water in human-dominated landscapes, increasing the likelihood of human elephant interaction and conflict (Leimgruber et al., 2003). In today's scenario, expanding agriculture and infrastructure and their prolonged impacts have fragmented and degraded elephant habitats due to which HEC is more pervasive than ever (MadhuSudan et al., 2015). Elephants, being generalist herbivores, often find high quality forage in agricultural areas, leading to frequent crop- raid incidents, which creates significant economic losses for local communities (Suba et al., 2020) and often provoke retaliatory actions against elephants, including electrocution and poisoning (LaDue et al., 2021). The escalating human-elephant conflict underscores the urgent need for effective mitigation strategies to safeguard both human livelihoods and elephant populations (Bhagat et al., 2017).

In Central Indian landscape, especially Chota Nagpur Plateau, where forested areas are patchy and interspersed with rural settlements, elephants frequently traverse cultivated lands, resulting in increased conflict with residents (Mandal and Das Chatterjee, 2023). Human and elephant deaths, property damage, and psychological stress to local communities are all consequences of HEC that go beyond financial losses (Shaffer et al., 2019). Between 2010 and 2020, India experienced a significant number of human fatalities due to elephant encounters, with states like Jharkhand reporting some of the highest incidences (Guru and Das, 2021). In Jharkhand, the length of National Highways expanded from 2,402 km in 2014 to 7,791 km by 2018, reflecting rapid infrastructure development. The total area under irrigation canals in the state amounts to approximately 560.54 hectares, as reported by the Water Resource Department of Jharkhand. According to the Forest Survey of India (FSI) in 1999, elephant habitats in Jharkhand covered about 6,000 sq km, supporting a population of 600–700 elephants. However, according to the Ministry of Environment, Forest and Climate Change (MoEF&CC) 2017 report, the elephant population in Jharkhand was estimated at approximately 679 individuals, the habitat area has reportedly been reduced to around 3,800 sq km (Khan et al., 2023). This contraction of habitat, coupled with increased human activities, underscores the escalating human-elephant conflicts in the region. Elephants are known to travel long distances each year from Jharkhand's Singhbhum and Dhalbhum forest regions into the neighboring states of West Bengal, and Odisha (Palei et al., 2016). However, this region has undergone rigorous changes due to building highways, railways, canals leading to mining, and changing agricultural practice (Latif and Palita, 2023). Due to such anthropogenic stressors elephants have ventured into areas of Hazaribagh, Ranchi, Ramgarh, Bokaro, and Dhanbad (Menon et al., 2017). The stay spans of migrating elephants from Dalma Wildlife Sanctuary, Jharkhand to Panchet Forest Division, West Bengal increased with successive years (Chatterjee and Chatterjee, 2014; Chatterjee and Mandal, 2019). The limited scattered forest patches, with interspersed agriculture land use in and around, affect the movement of elephants during the monsoon season, and have become a cause of concern for human-elephant conflicts (Khanna et al., 2001; Shaffer et al., 2019). The dynamic and evolving nature of HEC necessitates understanding not only current patterns but also historical trends to inform effective conflict mitigation strategies. A fundamental knowledge of the patterns and influences that have molded modern HEC can be gained from historical data. Spatial and temporal patterns using longitudinal data on land-use changes, conflict events, and elephant and human death. This information can be crucial for comprehending how conflict hotspots develop over time (Leimgruber et al., 2003). Furthermore, understanding historical patterns allows for assessing the long-term effectiveness of mitigation strategies, revealing whether certain interventions have reduced or inadvertently intensified conflict (Fernando et al., 2008). In the present study, the following research questions specific to the scenario of elephant mortality in Jharkhand: (i) How have the causes of elephant mortality and their spatial distribution across Jharkhand shifted over the past two decades (2000–2023)? (ii) Is there a significant association between the age and demographic characteristics of deceased elephants and specific causes of mortality, with a focus on anthropogenic stressors? (iii) How have changes in land use and land cover (LULC) during this period potentially influenced these mortality patterns? This study hypothesizes that changes in LULC including modifications to natural vegetation, landscape fragmentation, intensification of agriculture, and urbanization—are major predictors of HEC in Jharkhand (Lambin et al., 2001). It is also anticipated that proximity to protected areas and the rapid expansion of linear infrastructures (e.g., roads and railways) contribute to an increased frequency of conflict incidents (Johnsingh and Williams 1999; Sukumar, 2003; Ramesh et al., 2022). Other factors potentially degrading elephant habitats include intensive cattle grazing at forest edges and limited distance from water sources. The results of this study aim to provide a comprehensive framework for mitigating HEC in Jharkhand, reducing both elephant and human casualties. By informing policy and guiding land-use planning, this research offers strategic solutions to support the long-term conservation of elephants within Jharkhand's increasingly fragmented landscape.

2 Study area

The study area for this research is Jharkhand, India, which lies between 21°58' to 25°18' N latitude and 83°22' to 87°57' E longitude (Figure 1). Jharkhand covers a geographical area of approximately 79,714 km², with forested regions making up around 29.5% of its area (Forest Survey of India, 2019). Jharkhand's climate is primarily tropical with three main seasons: a hot summer from March to June, a monsoon period from July to September, and a cooler winter from October to February. Summer temperatures can rise to 47 °C, while winter temperatures can drop

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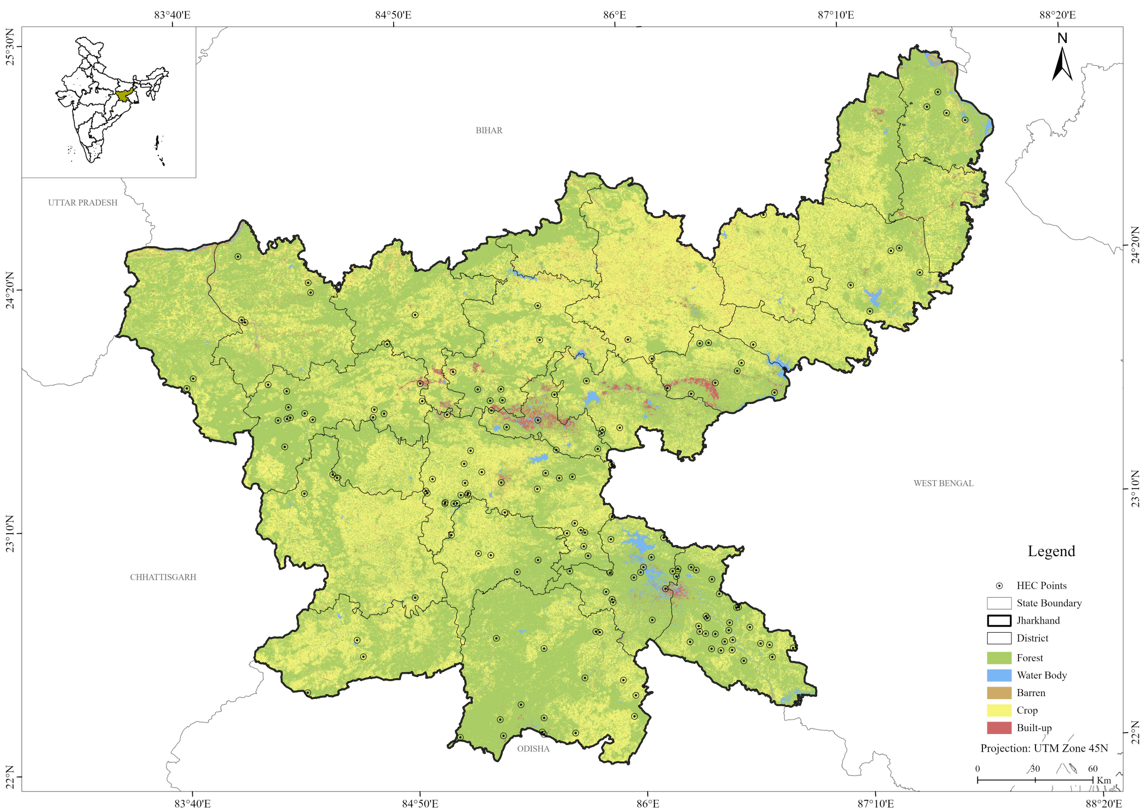

FIGURE 1
Study area Map of Jharkhand State, India, with Land cover Land use types and location of elephant deaths from 2000 – 2023. The map was created using ArcGIS Pro version 3.0.0 (https://www.esri.com/enus/arcgis/products/arcgis-pro/overview).

as low as 3 °C (Ahmad et al., 2018). The average annual rainfall in Jharkhand is about 1,400 mm, with most precipitation occurring during the monsoon months (Pandit et al., 2023). Jharkhand's landscape is separated into three major physiographic zones: Chotanagpur Plateau, Ranchi Plateau, and Kolhan Plateau. The Chotanagpur Plateau is rich in forest resources, with both tropical moist and dry deciduous forests. These forests support a varied range of flora and animals, including elephants, which rely on them for food, water, and migration corridors (Naha et al., 2019). However, in recent decades, this region has seen significant land-use change, especially due to mining and urbanization (Ahmad and Dey, 2017; Singh, 2020). Between 1990 and 2020, massive increase of coal and iron ore mining in areas like as Dhanbad, Bokaro, and West Singhbhum resulted in major forest degradation, threatening biodiversity and elephant habitats (Singh and Upgupta, 2021). Logging, agricultural expansion, and rapid infrastructure development have significantly reduced and fragmented forest cover in regions such as Palamu and Latehar, further isolating elephant habitats and constraining their natural movement. Jharkhand is rich in mineral resources such as coal, iron ore, bauxite, and uranium, which contribute significantly to the state's economy (Indian Bureau of Mines, 1968). However, mining activities have resulted in environmental challenges like deforestation, soil erosion, water pollution, and habitat fragmentation, harming both animal and human populations (Ranjan, 2019). These anthropogenic pressures have led to a rise in HEC incidents, as elephants often move outside of protected forest areas in search of food and water, encountering human settlements along their migratory routes (Natarajan et al., 2025). As a result, Jharkhand has witnessed frequent incidents of crop raiding, property damage, and occasional human fatalities, placing immense socio-economic strain on local communities and escalating tensions between people and wildlife (Tripathy et al., 2021).

The state's population has grown from approximately 32.96 million in 2011 to around 38 million in 2023, increasing the demand for land and resources (CENSUS OF INDIA, 2011). This demographic growth, combined with industrial expansion, has intensified HEC, especially in areas where agriculture encroaches on elephant habitats (Natarajan et al., 2025). Many rural and tribal communities in districts like Gumla, Simdega, and Dumka depend on agriculture and forest resources for their livelihoods, making them vulnerable to HEC incidents, which impact local economies and community safety (Sahu, 2019). This socio-economic dependency on land and resources often overlaps with critical elephant habitats, creating a complex landscape where HEC and elephant mortality are prominent. Additionally, the state has a history of elephant mortalities due to electrocution, accidents with trains, and retaliatory actions, underscoring the need for a thorough understanding of mortality patterns and conflict drivers to develop effective mitigation strategies (Khan et al., 2023). Given these factors, Jharkhand serves as an essential case study to investigate the intricate relationship between human development, elephant habitat-use, and the resulting conflicts. By examining the spatial and temporal patterns of elephant mortality, this research aims to inform conservation strategies that can balance the needs of both wildlife and local communities in Jharkhand's dynamic landscape.

3 Methods

3.1 Data analysis

A database documenting 225 elephant mortality cases was compiled from 22 forest divisions of Jharkhand over a 23-year period (2000-2023). Each mortality case was categorized based on: (1) cause of death, (2) time of incident (year, month, and season: monsoon, post-monsoon, summer, and winter), (3) division-wise distribution, and (4) age and demographic details of the deceased elephant. The causes of death were further classified (see Supplementary Table 1), with accidental deaths encompassing incidents caused by natural calamities such as drowning, lightning strikes, falls from hills, and illness. Age groups were categorized as calves (0–1 year), juveniles/yearlings (1–5 years), sub-adult males and females (6–15 years), and adult males and females (16+ years) following Arivazhagan and Sukumar (2008). The research team visited the respective forest divisions and scrutiny was undertaken to collect and verify the data from the forest divisions. The data were verified across divisions through cross- verification with respective Forest Department Offices, and duplicate or uncertain entries were carefully identified and removed to ensure accuracy in the final analysis.

3.2 Land use and land cover change & influencing factors of elephant mortality

The data was analyzed in five-year intervals (2000–2005, 2005–2010, 2010–2015, 2015–2020, and 2020–2024) using Landsat 5 TM and Landsat 8 OLI satellite imagery (2000–2023) at a 30 m spatial resolution (Figure 2). The classification process utilized six spectral bands (blue, green, red, NIR, and two SWIR), while the QA band was applied for cloud and shadow masking. For each 5 classes, a total of 1,250 random points were collected for training and validation of the Random Forest (RF) classifier, with 70% used for training and 30% for validation in each iteration. Accuracy assessment was conducted to evaluate classification performance. Image processing and classification were performed using Google Earth Engine (GEE), while ArcGIS Pro was used for sub-setting, fragmentation analysis, distance measurements, and map preparation. The Landsat dataset was classified using a supervised pixel-based RF algorithm from the "smileRandomForest" library in GEE, mapping five land-use/land-cover (LULC) categories: (1) forest, (2) waterbodies, (3) barren land, (4) croplands, and (5) built-up.

To assess forest fragmentation, Patch Density (PD), Edge Density (ED), and Largest Patch Index (LPI) were extracted from the LULC maps using FRAGSTATS v.4.2 (McGarigal et al., 2012. The LULC layers were categorized into five-year intervals and resampled to a 100 m spatial resolution to ensure consistency across all time periods. Each raster was then converted into a binary map, assigning a value of 1 to forest pixels and 0 to non-forest pixels. A circular moving window with a 7 km radius was applied to calculate localized fragmentation metrics around each forest pixel as this corresponds to a daily movement of elephants around ~7 km (Cushman et al., 2010; Brady et al., 2021; Chan et al., 2022). The spatial distribution of elephant mortality was analyzed through kernel density estimation in ArcGIS Pro to identify mortality hotspots across divisions and villages. To determine the impact of ecological and anthropogenic factors on elephant mortality, Generalized Linear Models (GLMs) with a binomial distribution were applied in R (version 4.3.1). Mortality incidents (excluding natural deaths) were coded as 1, while pseudoabsence locations (coded as 0) were generated. A total of 225 random points (pseudo absence points) were generated within the study area using the "Create Random Points" tool in ArcGIS Pro. Subsequently, any random points located within a 1 km buffer of actual incident points were removed to ensure spatial independence between random and incident locations.

The GLM analysis included 12 explanatory variables: distances to forests, croplands, built-up areas, roads, railways, mines, water bodies, protected areas, and elephant reserves, along with edge density, patch density, and the largest patch index derived from FRAGSTATS. The hypotheses for the variables used in the GLM analysis are outlined in Table 1. LULC classification was carried out at five-year intervals, Correspondingly, elephant mortality data were also grouped into the same five-year intervals and above-mentioned predictor variables were extracted. Subsequently, Generalized Linear Models (GLM) were fitted using a binomial distribution with a logit link function, as the response variable (elephant mortality) was binary (death = 1, absence = 0). Model selection was conducted through univariate analyses assessing the significance of each predictor, followed by collinearity checks were done and retained variables which were ecologically explainable and removed other highly correlated variables. Model performance was evaluated using Akaike Information Criterion (AIC), with models having $\Delta AIC \leq 2$ considered well-supported (Burnham and Anderson, 2002). The final model was selected based on the lowest AIC value, ensuring an optimal balance between explanatory power and parsimony. The "MuMIn" package in R was used for model ranking.

3.3 Village categorization for elephant mortality

To examine the spatial distribution of elephant mortality in Jharkhand, villages were categorized into three risk levels: low (0–2

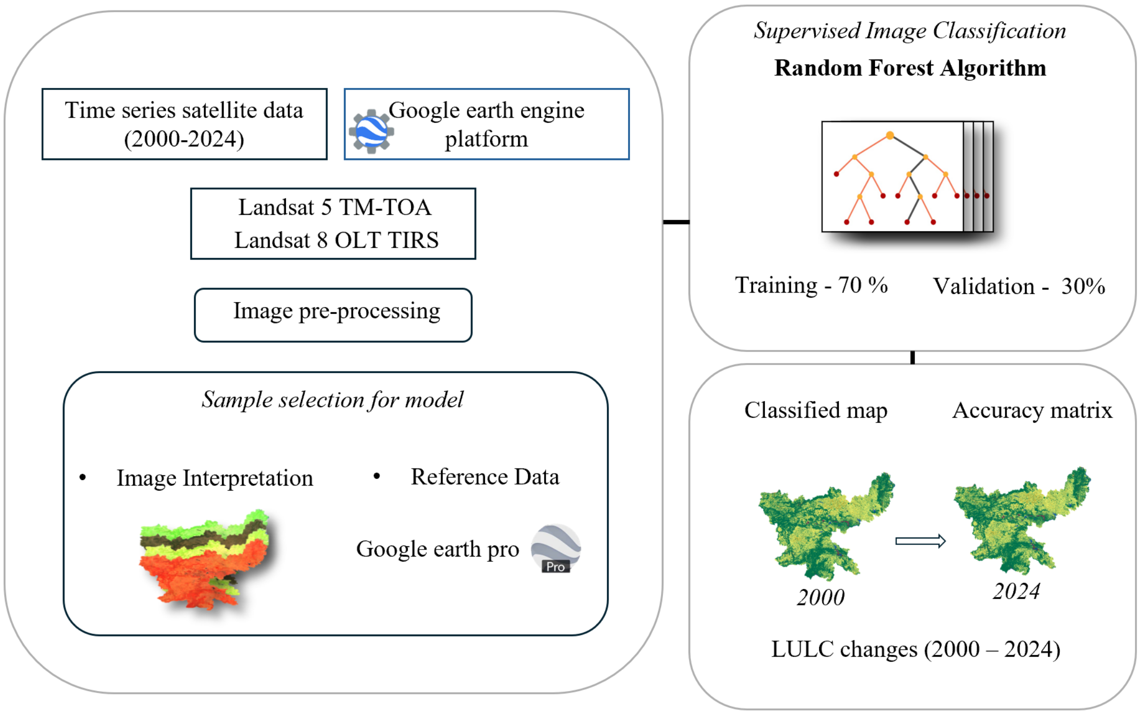

FIGURE 2
Flow chart showing methodology of Land Use Land Cover classification and analysis.

deaths), medium (2–5 deaths), and high (more than 5 deaths). This classification helps in identifying key environmental factors influencing elephant mortality, including forest cover percentage, crop cover percentage, mine percentage, number of water bodies, percent built-up area, road density and railway density. Understanding these spatial patterns enables targeted conservation and mitigation strategies, particularly in high-risk areas, focusing on habitat restoration, human-elephant conflict management, and infrastructure planning to reduce mortality incidents. The village boundaries were obtained from the ArcGIS Online, shapefile: Indian Administrative Layer 2024.

4 Results

4.1 Temporal trends and land use land change patterns in elephant mortality

The land cover change analysis from 2000 to 2024 showed changes in forest cover, water bodies, barren land, cropland, and built-up areas. Forest cover showed a constant change, decreasing from 48,440 sq.km in 2000 to 41,194 sq.km in 2024. Cropland expanded significantly, peaking at 41,628 sq.km in 2015 (+23.36%) before falling to 29,239 sq.km in 2024 (-1.76%). Built-up increased over the years, with the highest surge observed between 2020 and 2024 (+93.34%). Additionally, transition matrix highlighted the conversion of forest cover primarily to cropland (33.2%), built-up areas (1.17%), and barren land (1.3%), while cropland has been converted to built-up areas (7%) and other land categories (Figure 3) (Supplementary Table 2). The forest fragmentation metrices analysis for 2024 showed, large forest patches remain intact the southeastern region, while central and southwestern areas exhibit high edge density and fragmentation (SF1).

4.2 Temporal trends and spatial distribution of elephant mortality

During the 23 years span, a total of 225 cases of elephant mortality were reported. Among them 73 cases were from natural deaths (including natural death: 60 and Territorial fight: 13) and Anthropogenic cases: 152 (including Accidental deaths: 13; Anthropogenic stressor: 33; Electrocution: 67; Landmine blast: 1; Poaching: 4; Poisoning: 11 Retaliation killing: 1; Train hit: 17; Vehicular Accident: 5). The highest number of deaths were reported in the year 2022 (SF2 & SF3). Electrocution emerged as the main cause of the elephant mortality (χ^2 = 2.131, df = 1, p-value = 0.144). Distribution of age group due to anthropogenic causes differed significantly (χ^2 = 19.158, df = 5, p-value = 0.0017), with adult male (39) having the highest number of mortalities, followed by adult female (35), sub adult male (22), yearling (21), sub adult female (15) and calf (19) (Figure 4). Monsoon (56 deaths) accounts for the most elephants' deaths (χ^2 = 44.382, df = 4, p-value < 0.05), followed by post-monsoon (43), winter (33) and pre-monsoon (20). Ranchi division (30 deaths) had the highest number of deaths with electrocution (16 deaths) and train hit (3 deaths), then East

TABLE 1 *A priori* hypotheses for all environmental and anthropogenic variables for corelating elephant deaths.

Feature	Variable	Description and source	A-priori hypothesis
Landcover	Distance from Built-up (db)	Classified landcover types, such as built-up areas, cropland, forests, and waterbodies, were used to calculate distances between conflict points and each landcover type using the Near Table tool in ArcPro 3.0.0.	Higher elephant mortality near settlements due to increased human-elephant interactions.
	Distance from Cropland (dc)		Proximity to cropland increases mortality risk due to electrocution and retaliation.
	Distance from Forest (df)		Mortality risk decreases with distance from forests, which provide essential resources.
	Distance from Waterbodies (dw)		Proximity to waterbodies lowers mortality risk by reducing movement into human areas.
	Edge density(ed)	Edge density represents the total length of transitions between different landcover types per unit area. The value is extracted using "Extract Multi Values to Points" tool in ArcGIS Pro 3.0.0.	Higher edge density increases mortality risk due to habitat fragmentation and human interaction.
	Largest Patch Index (lpi)	The Largest Patch Index measures the size of the largest continuous habitat patch within a landscape. The value is extracted using "Extract Multi Values to Points" tool in ArcGIS Pro 3.0.0.	Elephants near large habitat patches have lower mortality risk due to resource availability.
	Patch Density (pd)	The Patch Density quantifies the number and distribution of habitat patches within a landscape. The value is extracted using "Extract Multi Values to Points" tool in ArcGIS Pro 3.0.0.	Higher patch density increases fragmentation and human-elephant conflicts.
	Distance from Mining Areas (dmn)	Mining area boundaries were digitized from google earth pro using GIS spatial analysis. Distances were calculated using the Near Table tool in ArcPro 3.0.0.	Mortality risk increases near mining areas due to habitat destruction and increased human presence.
Anthropogenic	Distance from Railways (drail)	Road and railway network shapefiles were sourced from OpenStreetMap.org, with distances calculated using the Near Table too in ArcPro 3.0.0.	Close proximity increases mortality risk from train collisions and habitat fragmentation.
	Distance from Road (dr)		Higher mortality risk due to vehicle collisions and habitat disturbance.
	Distance from Protected Areas (dpa)	Distance between elephants and protected area boundaries was calculated using shapefiles from the Elephant Cell at the Wildlife Institute of India (WII), processed in ArcPro 3.0.0.	Lower mortality risk near protected areas due to reduced human pressure.
	Distance from Elephant Reserve (der)	Distances were measured between elephant reserves and conflict points to evaluate the role of these areas in mortality risk.	Lower mortality risk near reserves due to sufficient resources.

Singhbhum (18 deaths) with electrocution (18 deaths) then Saraikela division (14 deaths) with electrocution (11 deaths) (Figure 5). This pattern was also observed in the kernel density analysis, highlighting these areas as the hotspots for elephant deaths in the state (Figure 6).

4.3 Factors influencing elephant mortality and village characteristics

A total of 122 villages in the state reported elephant mortalities over a span of 23 years. This study revealed that high-incident villages did not show significantly higher built-up areas compared to medium and low-incident villages (Kruskal-Wallis: χ^2 = 2.31, p = 0.509; Figure 7A). However, high-incident villages had greater forest cover (χ^2 = 4.92, p = 0.177; Figure 7B). In terms of crop percentage, high-incident villages had significantly lower values compared to medium and low-incident villages (χ^2 = 4.88, p = 0.180; Figure 7C). Additionally, high-incident villages had lower water density compared to medium and low-incident villages (χ^2 = 0.82, p = 0.844; Figure 7D). High incident villages have lower road density, (χ^2 = 9.47, p = 0.023; Figure 7E). *Post hoc* Dunn's test showed significant difference between incident and low incident villages (p=0.012). There was no significant difference observed in forest cover, water density, built-up area, and crop cover. We also found that elephant mortality incidents were higher closer to water bodies (β = -1.080, p < 0.05), railway (β = -1.128, p = 0), forest and road (β = -7.419, p < 0.05). However, conflict incidents increase with increase in distance from built-up (β = 2.553, p = 0), protected area (β = 4.066, p=0) and mines (β = 3.298, p = 0); (Figure 8, Tables 2, 3).

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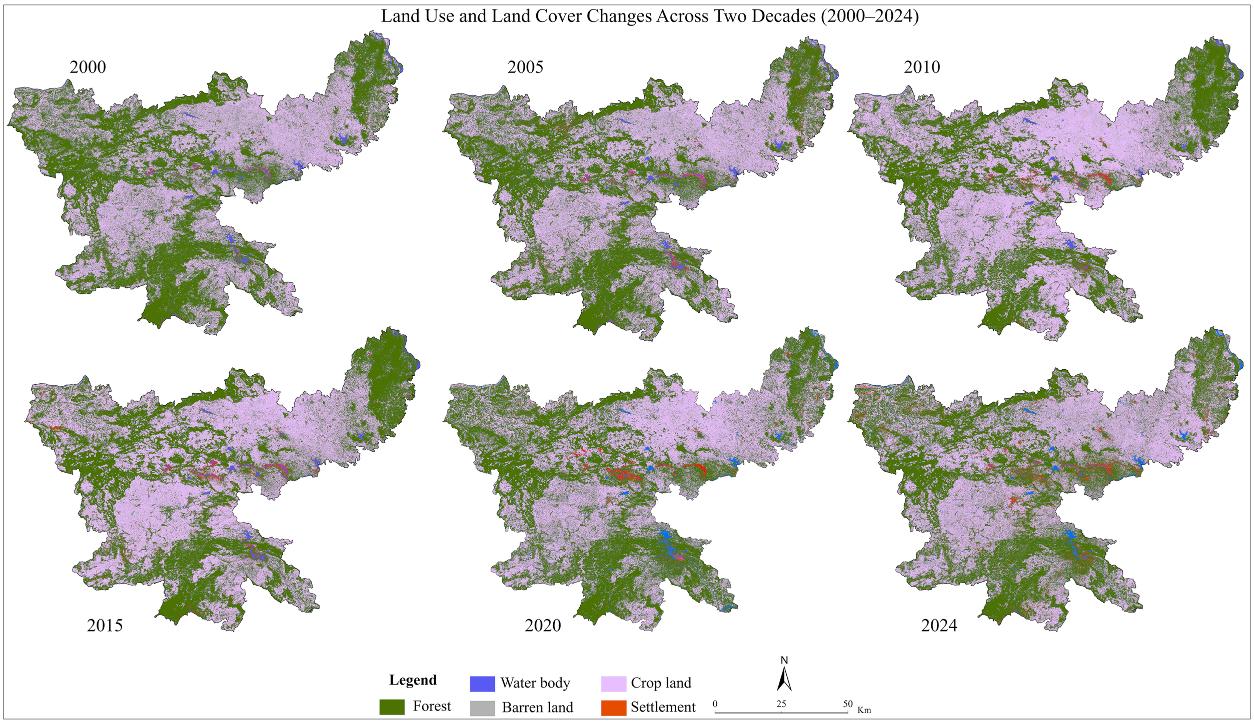

FIGURE 3
Land use Land cover maps of Jharkhand, India from year 2000-2024. The map was created using ArcGIS Pro 3.0.0 (https://www.esri.com/enus/arcgis/products/arcgis-pro/overview).

5 Discussion

From 2000 to 2024, forest cover exhibited a continuous decline, and an increasing trend in agriculture. Built-up areas showed significant growth, with the most rapid expansion occurring in recent years. The transition analysis indicated that forest cover was primarily converted into cropland, built-up areas, and barren land, while cropland also transitioned into built-up areas and other land categories. The findings align with broader patterns of land transformation driven by urbanization, agricultural expansion, and resource extraction in Jharkhand (Sharma et al., 2012). The spatial and temporal trends of elephant mortality in Jharkhand provide

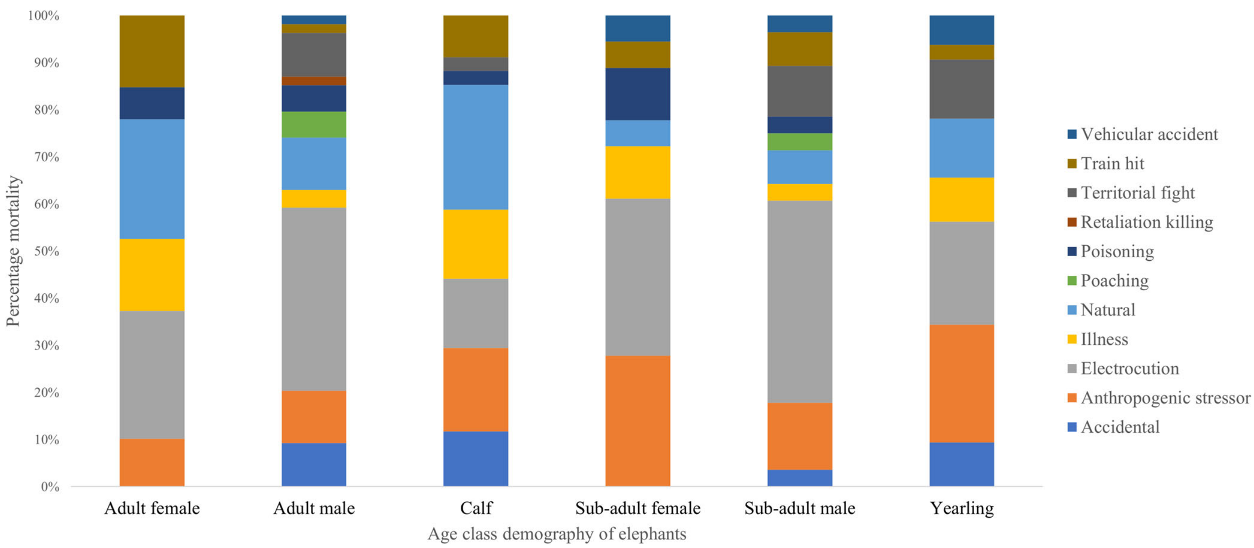

FIGURE 4
The graph illustrating the relation between the causes of elephant mortality and age class demography of Jharkhand, India from 2000-2023.

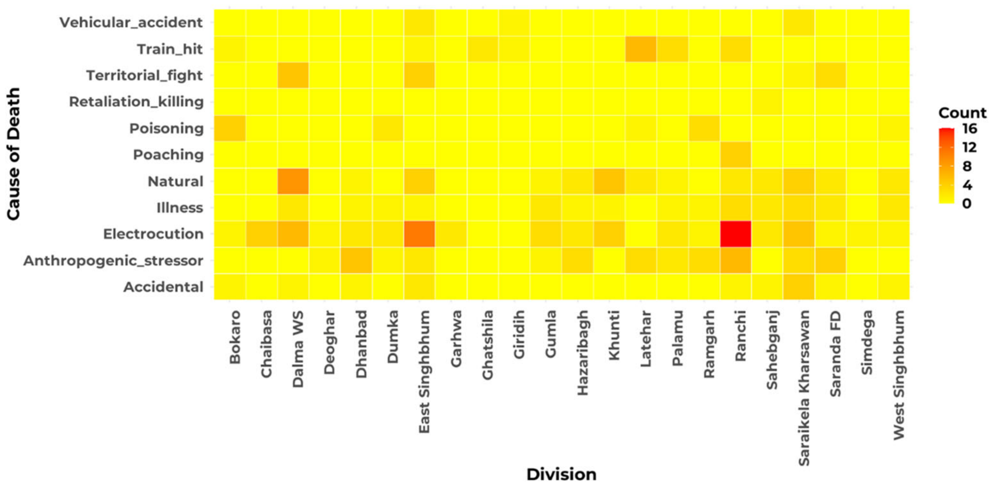

FIGURE 5
Heatmap showing spatial distribution pattern of Elephant mortality in different divisions of Jharkhand, India from 2000-2023.

insights into the different interactions between environmental and anthropogenic variables and land use land cover characteristics. This study reflects electrocution as the leading cause elephant mortality, accounting for most of the deaths particularly in Ranchi and East Singhbum which are also the hotspots for the elephant mortality in the state. This finding encompasses several studies that have identified electrocution as a major threat to elephant population in human dominated landscape (Goswami et al., 2015; Menon et al., 2017). Highest elephant mortality in the monsoon season highlights elephants' seasonal vulnerability due to increased human activities

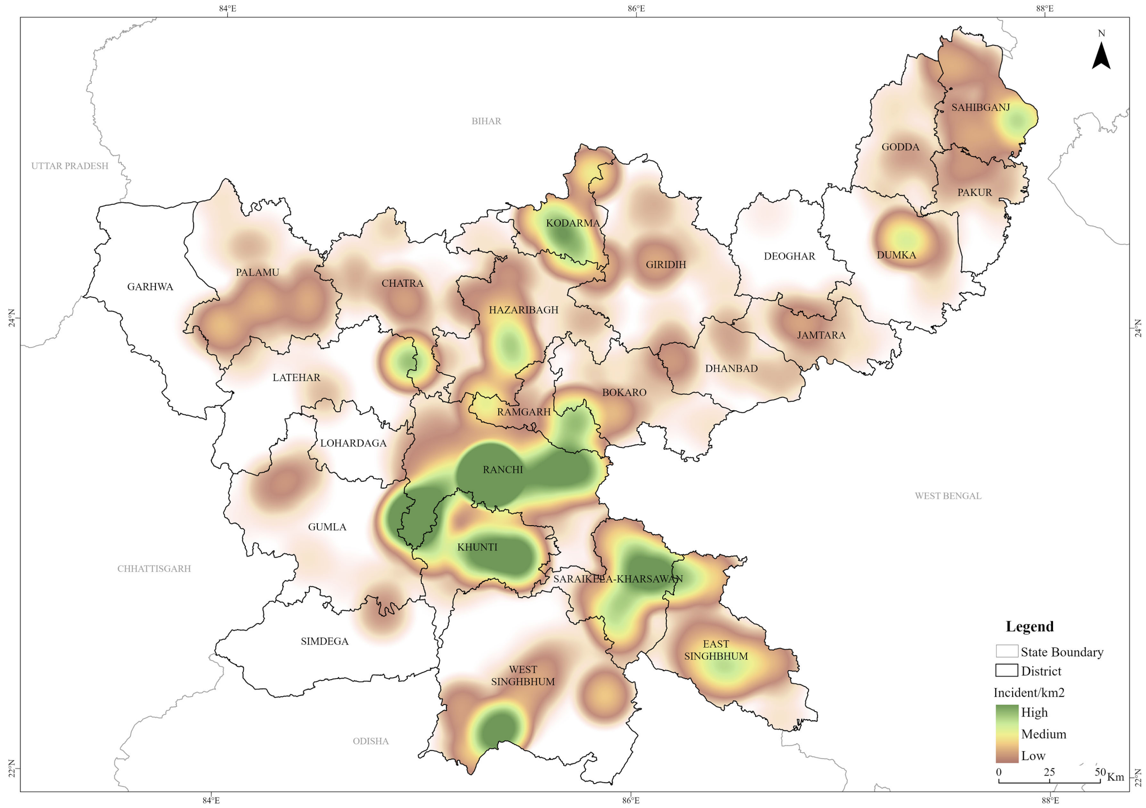

FIGURE 6
Kernel density map of Jharkhand highlighting high, medium and low mortality zones for elephant mortality of Jharkhand, India from 2000-2023. The was created using ArcGIS Pro version 3.0.0 (https://www.esri.com/enus/arcgis/products/arcgis-pro/overview).

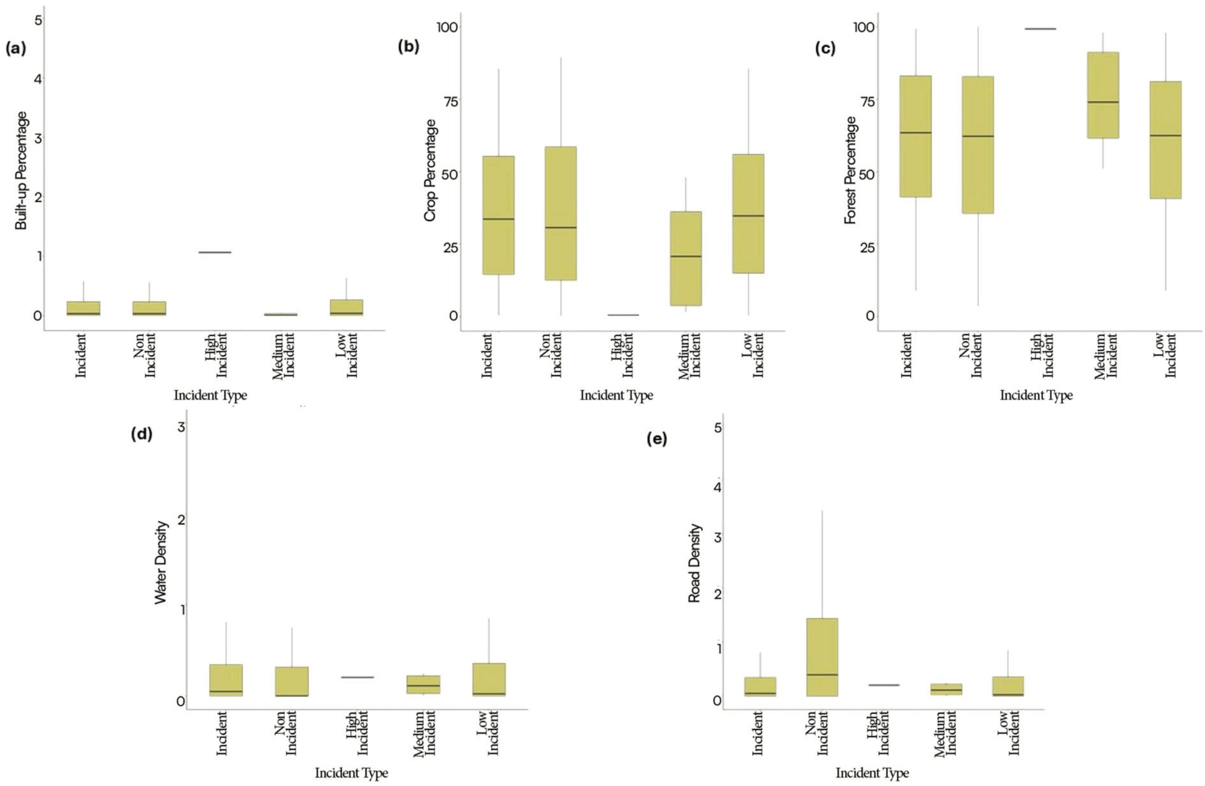

FIGURE 7
Figure showing variations of **(a)** Built-up area, **(b)** crop cover, **(c)** percent forest cover, **(d)** water density, and **(e)** road density in non, low, medium and high incident villages (incident = elephant mortality) in Jharkhand India.

(Baskaran et al., 2013; Fernando et al., 2005). This is likely driven by increased agricultural activities and elephant movement in monsoon (Fernando et al., 2005). Adult males and females exhibited highest mortality rates, consistent with findings suggesting adult elephants venture in human- dominated areas in search of resources increasing their exposure to anthropogenic threats (Desai and Baskaran, 1996; Sukumar, 2003). A similar trend observed in north Bengal where adult males face higher mortality because they are more prone to entering human- dominated areas for resource (Mitra, 2017). The concentration of elephant mortality in regions like Ranchi and East Singhbum, that are characterized by fragmented landscapes and high human activity, aligns with the study showing a strong link between mortality, habitat fragmentation, and proximity to human settlements (Fernando et al., 2008; Vasudev et al., 2020). Jharkhand has 17 identified elephant corridors, the third highest in India. Notably, Singhbhum Elephant Reserve has 14 corridors, but only 38% of it is forested, and it reports one of the highest HEC levels in India (Pandey et al., 2024).

High-incident villages have more built-up areas and forest cover, but less cropland and lower road density. This indicates that elephant presence is higher where forests and human infrastructure overlap, increasing the risk of conflict. This is consistent with the studies that have linked elephant mortality to encroachment of human's settlements into elephant corridors and habitat fragmentation (Goswami et al., 2015; Leimgruber et al., 2003). Fragmented habitats force elephants to move through human dominated landscapes, exposing them to risks such as electrocution, vehicle collision and retaliatory killing (Leimgruber et al., 2003; Sitati et al., 2003). The lower crop cover in high-incident villages aligns with the idea that elephants in these areas are often moving through transitional zones between forests and human settlements, where agricultural activity is less but human infrastructure (such as power lines and roads) is more prevalent. This pattern has been observed in Sri Lanka, where elephants moving through fragmented landscapes faced higher mortality risks due to encounters with human infrastructure. Similarly, the lower water density in high-incident villages may reflect the scarcity of natural water sources, forcing elephants to travel greater distances and increasing their exposure to anthropogenic threats (Fernando et al., 2005). The lower road density in high-incident villages suggests that even limited infrastructure can have a disproportionate impact on elephant mortality. This finding is consistent with studies where even low-density road networks in fragmented landscapes can significantly increase elephant mortality due to vehicle collisions and other human-related threats (Goswami et al., 2015; Lakshminarayanan et al., 2016). For every 1km increase in distance from forest areas, the elephant mortality decreased by `73.6% suggesting mortality incidents occurred closer to forest edges where elephants are more likely to encounter human activities, infrastructure etc. Elephant mortality is closely linked to distance from protected areas. Elephants are more at risk in areas far from these zones, likely due to greater exposure to threats like

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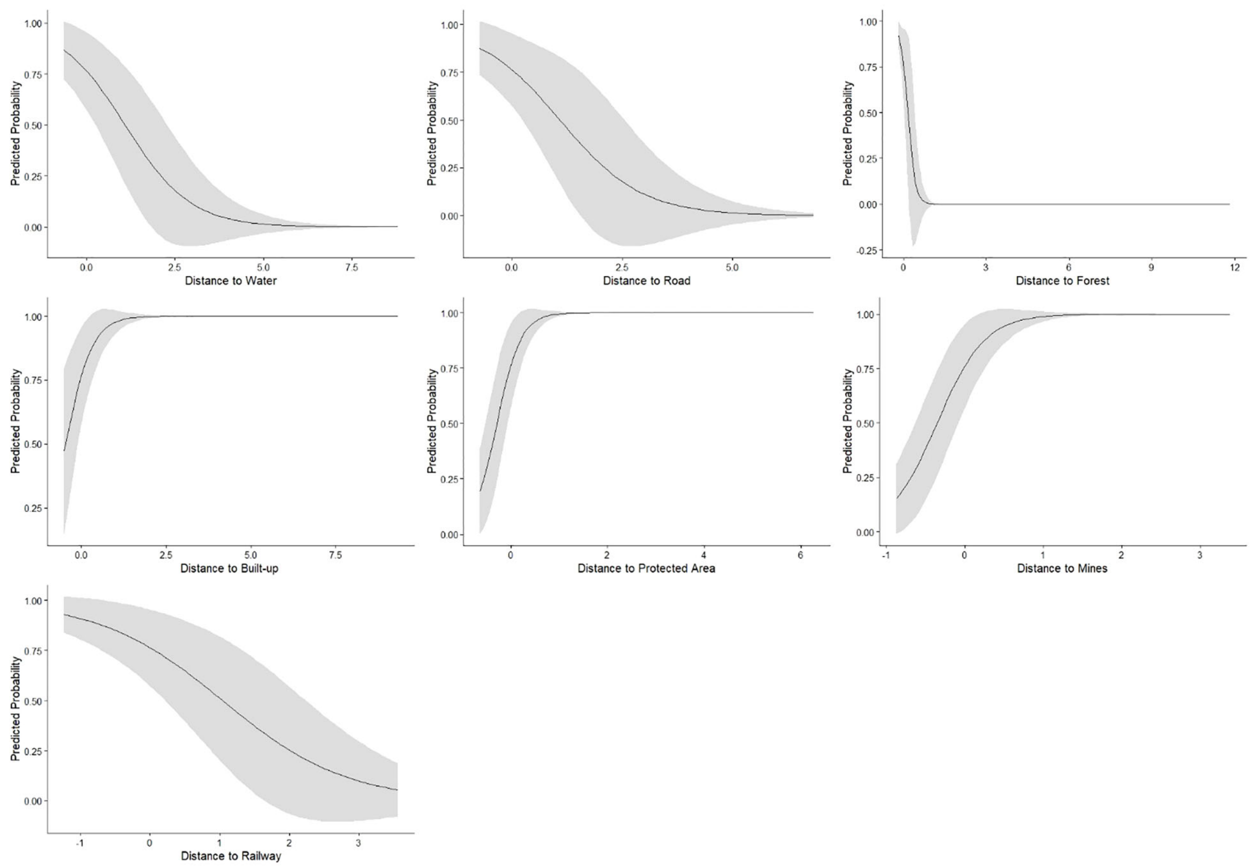

FIGURE 8
Graphs showing the probability of elephant death from distance from different variables or predictors of elephant mortality in the state of Jharkhand, India.

TABLE 2 Summary statistics loglikelihood (LogL), degrees of freedom (df), Akaike Information Criteria (AICc), relative support for hypothesis (Δ AICc), Akaike weights (Wi) of candidate regression model explaining elephant mortality in Jharkhand.

Model Description	LogL	df	AICc	ΔAICc	Wi
dw + dr + df + db + dpa + dmn + drail	-51.94	8.00	120.37	0.00	0.96
dw + dr + df + dc + db + der + dpa + dmn + lpi + drail	-51.81	11.00	126.52	6.15	0.04
df + dc + db + dmn + dpa + lpi	-71.75	7.00	157.87	37.50	0.00
dpa + df + dc + dmn + lpi	-75.44	6.00	163.17	42.80	0.00
dw + df + db + dmn + drail	-86.49	6.00	185.27	64.90	0.00
dr + db + der + dc + dpa	-94.46	6.00	201.21	80.84	0.00
dr + db + dc + der + dmn + lpi	-95.93	7.00	206.23	85.86	0.00
dw + dr + df + dmn + lpi + drail	-96.41	7.00	207.20	86.83	0.00
df + db + dc + dmn	-99.69	5.00	209.59	89.22	0.00
dmn + drail	-103.12	3.00	212.32	91.95	0.00
dmn + df + dr + lpi	-108.67	5.00	227.55	107.18	0.00
Dmn	-114.25	2.00	232.53	112.16	0.00
dmn + dc + lpi	-112.97	4.00	234.07	113.70	0.00
dw + df + dr + db + der + drail	-121.48	7.00	257.34	136.97	0.00
Null	-211.41	1.00	424.83	304.46	0.00

TABLE 3 Parameter estimates effect (β) and probabilities of ecological and anthropogenic variables in determining mortality of Asian elephant due to various anthropogenic activity.

Predictor	Beta Coefficient (β)	Z value	P value	Significance
(Intercept)	1.174	2.172	0.03	*
Distance to waterbodies(dw)	-1.080	-3.119	0.00	**
Distance to roads (dr)	-1.079	-2.440	0.01	*
Distance to forest (df)	-7.419	-2.402	0.02	*
Distance to builtup (db)	2.553	2.972	0.00	**
Distance to Protected area (PAs)	4.066	5.073	0.00	***
Distance to mines (dmn)	3.298	4.559	0.00	***
Distance to railways (drail)	-1.128	-3.332	0.00	***

*: P ≤ 0.05 (Statistically Significant), **: P ≤ 0.01 (Moderately Significant), ***: P ≤ 0.001 (Highly Significant).

poaching, electrocution, and vehicle collisions. This aligns with studies from Africa and Sri Lanka, which have shown that elephants outside protected areas face higher mortality risks due to human activities (Blake et al., 2008; Fernando et al., 2005). Forest elephants in the Congo Basin experienced higher mortality rates in areas with road networks and human settlements, as these landscapes increased their exposure to poaching and other threats (Blake et al., 2008). Similarly, elephants in Sri Lanka were more likely to die in areas with high human density and low forest cover, further emphasizing the importance of protected areas in reducing mortality risks (Fernando et al., 2005). Elephant deaths were more prevalent in areas with accessible water sources, which aligns with the tendency of elephants to frequent these areas during dry periods. This suggests that ensuring the availability of water within forested regions could help reduce conflict by encouraging elephants to remain in their natural habitats during the dry season (Khan et al., 2023). Similarly, the decline in elephant mortality probability with increasing distance from roads and railways supports the findings of Rani et al. (2024) and Sukumar (2003), who emphasize the role of infrastructure in escalating HEC. The presence of roads and railways fragments elephant habitats and forces elephants into human-dominated areas, increasing conflict. This study also highlights the importance of implementing speed restrictions on railways to reduce train-elephant collisions, a significant issue in Jharkhand. The analysis did not reveal any negative relationship between elephant mortality and the presence of mines. However, previous studies have indicated that mining activities can escalate human-elephant conflict in surrounding areas (Bhengra and Mundri, 2019). It is important to note that our data specifically focused on recorded elephant deaths and may not fully capture the broader intensity or frequency of human-elephant conflict across the state. This is particularly relevant in Jharkhand, where extensive mining areas exacerbate HEC. Restoration of habitats around mining areas could help reduce these conflicts. The significant decline in conflict probability with increasing distance from forests supports the findings of Shaffer et al. (2019), who emphasize the importance of maintaining forest connectivity to mitigate human-elephant conflict. Fragmented forests elevate the risk of elephants entering human settlements.

6 Conclusion

Over the past 23 years, elephants in Jharkhand have faced growing threats from human-elephant conflict, habitat loss, and electrocution, with adult males and the monsoon season being particularly vulnerable. Areas like Ranchi, East Singhbum, and Saraikela have seen high mortality rates, underscoring the need for urgent conservation action. Jharkhand's unique position as a transitional zone for elephant populations moving between Odisha and neighboring states adds another layer of complexity to the issue. To address these challenges, several practical measures can be implemented. Several villages like Khokhro, Tokisud, Ghatshila, Musabani, Khelarisai, Adityapur falls in the Dalma- Asanbari and Dalma-Chandil corridor. Restoring and protecting critical elephant corridors is essential to ensure safe passage for elephants migrating between states. Implementing large-scale plantation drives in and around elephant corridors using native species, which require minimal maintenance, can help provide natural food sources for elephants. Clearing vegetation on both sides of railway tracks (30 m) for enhancing the visibility and reducing accidental encounters. Establishing a robust communication framework between railway authorities and wildlife conservation agencies is crucial. Installing elephant trackers near tracks and sensitizing train crews on emergency response protocols for preventing accidents. Effective measures like insulating power lines, building wildlife-friendly infrastructure, and creating underpasses or overpasses along railways and highways at known elephant crossing points should be strategically placed based on elephant movement patterns, that will significantly reduce accidents and deaths. Engaging local communities through early warning systems, compensation programs, and awareness campaigns can help build trust and reduce conflicts, especially in villages where human-elephant interactions are frequent. Technology can also play a key role—tools like AI-based monitoring, and GPS-enabled collars can track elephant movements in real time, providing early alerts to communities and forest officials. Strengthening policies, improving land-use planning, and fostering collaboration between states are equally important to ensure a coordinated approach to conservation. Through these combined efforts, Jharkhand can

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significantly reduce elephant mortality and human-elephant conflict, while also strengthening its role as a crucial corridor for elephants traversing state boundaries—paving the way for a safer coexistence between people and wildlife.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

RP: Formal analysis, Resources, Project administration, Visualization, Methodology, Validation, Investigation, Software, Supervision, Writing – review & editing, Conceptualization. KR: Formal analysis, Writing – original draft, Data curation, Methodology. AG: Visualization, Formal analysis, Data curation, Writing – original draft, Methodology. AD: Writing – review & editing, Data curation. DM: Investigation, Writing – review & editing, Validation, Project administration. PN: Writing – original draft, Methodology, Investigation, Writing – review & editing, Funding acquisition, Project administration. AN: Visualization, Data curation, Formal analysis, Writing – original draft, Investigation, Validation, Methodology, Writing – review & editing, Supervision. BH: Conceptualization, Methodology, Visualization, Validation, Resources, Software, Investigation, Data curation, Writing – review & editing, Funding acquisition, Supervision, Formal analysis, Project administration, Writing – original draft.

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