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Assessing the contribution of Indian zoos to achieving international biodiversity conservation goals

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Abstract
Zoos, are increasingly recognized as strategic actors in global biodiversity conservation, particularly under the Kunming-Montreal Global Biodiversity Framework (GBF) adopted under the Convention on Biological Diversity. As centers of conservation, education and public engagement, zoos are uniquely positioned to contribute to species conservation (Targets 2, 4, and 13), free-ranging biodiversity (Target 3), climate resilience through plant diversity (Target 8), urban biodiversity via green spaces (Target 12), and biodiversity education and awareness (Target 16). This study evaluates the role of 23 Indian zoos recognized by the Central Zoo Authority, testing empirically grounded hypotheses that link institutional characteristics such as zoo size, designated green area, captive species diversity, and visitor numbers with their contribution to biodiversity outcomes. Drawing from urban ecology, conservation biology, and education theory, supported by spatial and statistical analyses., the study highlights the potential of Indian zoos to serve not only as custodians of captive fauna but also as active players in habitat restoration, public sensitization, and green space enhancement. Key findings include a significant association between conservation breeding programs and the protection of threatened species, a positive correlation between green space and free-ranging mammal and bird richness, and a moderate link between visitor engagement and biodiversity education. These results offer valuable insights for policy alignment, strategic conservation planning, and the reimagining of zoos as urban ecological infrastructure.. Ultimately, this research underscores the importance of integrating zoos into national and state biodiversity action plans, positioning them as vital nodes in a broader conservation network that bridges ex situ stewardship, public education, and nature-based urban development.

Keywords Indian zoos, Kunming-Montreal global biodiversity framework, Central zoo authority, Species conservation, Biodiversity education, Urban green spaces, Climate resilience, Ex-situ conservation, Public engagement, Biodiversity awareness, Conservation planning, Habitat restoration, Urban ecology, Nature-based solutions

1 Introduction

Zoos have undergone a paradigm shift from mere recreational venues to pivotal hubs for global biodiversity conservation, education, and research. Historically rooted in showcasing exotic animals for public amusement—a practice dating back to ancient Egyptian menageries and later evolving into symbols of wealth and status [8]—zoos now prioritize biodiversity preservation amid the planet's sixth mass extinction, driven by habitat loss, climate change, and human activity [61]. Today, many zoos function as conservation centers equipped with extensive expertise that contributes directly to achieving Sustainable Development Goals (SDGs) and targets outlined in the Global Biodiversity Framework [9, 18, 67, 68]. As Spooner et al. [58] argue, the traditional four pillars of conservation, education, research, and recreation no longer fully capture the multifaceted role of modern zoos, which now operate at the heart of a web of conservation and societal engagement. Their potential to support communities and policy makers is increasingly recognized, though challenges remain in realizing their full impact. Modern zoos, particularly those accredited by organizations like the Association of Zoos and Aquariums (AZA), serve as critical centers for ex situ conservation, maintaining genetically diverse populations of endangered species as "modern-day arks" [15, 23, 38]. For instance, successful captive breeding programs in India—such as the gharial (*Gavialis gangeticus*) at the Nandankanan Zoological Park and Madras Crocodile Bank Trust (MCBT) and the mugger crocodile (*Crocodylus palustris*) in the National Chambal Sanctuary have increased population numbers by over 500% since 1970s, enabling reintroductions that prevent extinction these species from edging closer to extinction [54, 59]. These initiatives have provided critical insights into genetic management and reproductive biology, such as hormonal triggers for nesting in gharials, which inform broader conservation strategies [16]. These efforts are part of the broader global mandate of zoos to combat biodiversity loss and promote species recovery. By maintaining genetically diverse populations of threatened species, zoos serve as arks of hope for taxa facing severe threats in the wild due to habitat destruction, poaching, and climate change [15].

The conservation initiatives undertaken by zoos align with international frameworks such as the Convention on Biological Diversity (CBD) and the Kunming-Montreal Global Biodiversity Framework (GBF), which emphasize the need for active management actions to recover threatened species [16]. Through their breeding programs, research initiatives, and public education campaigns, zoos contribute to global biodiversity targets [15, 43] while fostering a deeper connection between people and the natural world. This integrated function of conservation and education underscores the importance of zoos as key institutions in the global effort to preserve biodiversity for future generations [29].

The Kunming-Montreal Global Biodiversity Framework (GBF), adopted at COP15 in 2022, marks a pivotal moment in global conservation policy, setting forth an ambitious agenda to halt and reverse biodiversity loss by 2030. Building on the lessons of the Aichi Biodiversity Targets, which fell short of their intended outcomes, the GBF introduces 23 action-oriented targets aimed at addressing both direct and indirect drivers of biodiversity decline, promoting sustainable use of natural resources, and fostering inclusive participation across sectors [16]. Framed as a "Paris Agreement for Nature," the GBF emphasizes science-based, collaborative approaches to conservation and recognizes the importance of diverse stakeholders—including zoos—in achieving its goals [58].

Zoos are uniquely positioned to contribute to several of these targets, particularly Target 4, which calls for urgent management actions to halt species extinction and ensure population recovery, and Target 12, which promotes the integration of biodiversity into urban planning and development. Through coordinated breeding programs, habitat restoration efforts, and public education campaigns, zoos serve as living laboratories and outreach centers that translate global policy into tangible local action. Their capacity to maintain genetically viable populations, conduct applied research, and engage communities makes them indispensable partners in implementing the GBF. Moreover, by fostering emotional and intellectual connections between visitors and wildlife, zoos help cultivate a conservation ethic that supports long-term behavioral change—an essential component of achieving the GBF's vision of living in harmony with nature by 2050 [29, 58].

2 Global context and comparative regulatory frameworks

Globally, zoos and aquaria are increasingly recognized as critical institutions for biodiversity conservation, education, and scientific research. These institutions operate under rigorous accreditation and regulatory standards designed to uphold animal welfare while contributing to national and international conservation goals [4]. In regions such as North America, Europe, and Australasia, frameworks established by the Association of Zoos and Aquariums (AZA), the European Association of Zoos and Aquaria (EAZA), and the Zoo and Aquarium Association (ZAA) respectively, have institutionalized species survival plans, ex situ population management, and welfare protocols grounded in scientific best practices [3, 34]. These models, while context-specific, have collectively influenced the evolution of zoo-based conservation approaches worldwide and contributed to achieving biodiversity objectives articulated in instruments such as the Convention on Biological Diversity (CBD) and, more recently, the Kunming–Montreal Global Biodiversity Framework [16].

These international frameworks emphasize integrated conservation strategies, including the safeguarding of genetic diversity (Target 4), equitable sharing of benefits from genetic resources (Target 13), and the strengthening of public education and awareness (Target 16). While many countries have adapted or developed national strategies to align with these targets, India's zoo governance—particularly through the Central Zoo Authority (CZA)—presents a case of early and proactive alignment with these global goals, even prior to the formal adoption of the GBF.

3 India's leadership in zoo governance: the role of the central zoo authority

Established in 1992 under Chapter IVA (Sections 38A–38J) of the Wildlife (Protection) Act, 1972, the Central Zoo Authority (CZA) was envisioned as India's apex statutory body to regulate, monitor, and guide the functioning of zoos across the country [25]. The CZA's mandate extended beyond animal care standards to include conservation breeding, genetic resource management, public engagement, and education—key pillars that have since found resonance in the GBF. The main objective is to oversee the functioning of Zoos in the country and to enforce minimum standards and norms for upkeep and health care of animals in Indian Zoos so that the Zoos come up to a standard where they can complement and strengthen the national efforts in conservation of wild fauna of the country.

Even before ex situ conservation became a central component of international frameworks, the CZA had initiated scientifically guided conservation breeding programs targeting endangered native species such as the Red panda (*Ailurus fulgens*), Asiatic lion (*Panthera leo persica*), and the Indian gharial (*Gavialis gangeticus*) [26]. These programs were explicitly designed not only to prevent demographic extinction but to also preserve genetic heterogeneity in captive populations, a principle now enshrined in Target 4 of the Kunming–Montreal Global Biodiversity Framework [16], which calls for the maintenance of genetic diversity within all wild and domesticated species. Concurrently, CZA launched the National Studbook Project in India in partnership with the Wildlife Institute of India, which enabled the compilation of pedigree records to guide genetic management strategies for key species in Indian zoos [42, 74]. Such measures are critical for ensuring that founder representation, inbreeding avoidance, and demographic stability are maintained over successive generations in captivity.

The CZA has identified 73 endangered species for inclusion in its Conservation Breeding Programme (CBP), each supported by a species-specific recovery plan that is explicitly linked to in situ conservation initiatives such as protected area management, habitat restoration and reintroduction strategies [11]. This ensures that ex situ efforts within zoos are not isolated but function as complementary components of broader species recovery frameworks. The CBP operates under the principles of the One Plan Approach, which emphasizes integrated planning across captive and wild populations through transdisciplinary collaboration involving zoos, field biologists, veterinarians, geneticists, and policy makers [69].

The Vision Plan-Zoos 2021 advances this model by embedding the concept of One Health, which recognizes the interconnectedness of human, animal, and ecosystem health [69]. Conservation breeding is positioned not only as a tool for species survival but also as a mechanism for enhancing ecological resilience and disease preparedness, particularly relevant in the context of zoonotic risks and climate-induced habitat shifts. By aligning CBP objectives with the Kunming-Montreal GBF, Indian zoos contribute directly to several targets: Target 4 (species recovery), Target 3 (conservation of free-ranging biodiversity), and Target 13 (genetic diversity preservation). Formal partnerships with scientific institutions ensure that breeding strategies are continuously informed by the latest ecological, behavioral, and genetic research.

The execution of these programs is structured around a hub-and-spoke system involving Coordinating Zoos and Participating Zoos:

1. **Coordinating Zoos** act as lead institutions for designated species and are mandated to develop and manage off-display planned Conservation Breeding Centers (CBCs). These CBCs are purpose-built to provide optimal breeding conditions while minimizing anthropogenic disturbance and stress from public display. Coordinating Zoos are responsible for maintaining comprehensive records, conducting genetic assessments, and coordinating animal transfers across institutions. They receive dedicated financial and technical support from the Central Zoo Authority (CZA) to establish and operate these centers [11].
2. **Participating Zoos**, in collaboration with the Coordinating Zoos, contribute to conservation breeding efforts by upgrading their enclosures and improving husbandry practices to support breeding programs or manage surplus populations. They also receive financial support from the Central Zoo Authority (CZA) to standardize

facilities in accordance with species-specific welfare standards and national conservation priorities [11].

3. The **CZA** functions as a *regulatory and coordinating body*, providing financial assistance, monitoring compliance, and ensuring the implementation of the National Zoo Policy 1998. It evaluates progress against predetermined conservation metrics and facilitates expert consultations for course corrections where necessary [10, 25].

This dual-tiered approach fosters a decentralized yet cohesive national network, ensuring optimal use of space, technical expertise, and species management across Indian zoos. It has also enabled streamlined genetic exchange, disease surveillance, veterinary standardization, and capacity-building through periodic training and workshops.

In addition to breeding-related infrastructure, the CZA mandates that at least 30% of a zoo's total area must be maintained as a dedicated green space [10, 69]. Green space refers to vegetated areas within urban and peri-urban environments—such as forests, grasslands, gardens, and landscaped zones, that are intentionally preserved or developed to support ecological integrity and human well-being. These spaces play a vital role in maintaining biodiversity, regulating microclimates, and enhancing the livability of cities [37]. In the context of zoological parks, green spaces are not merely aesthetic features but ecologically functional zones that provide habitat for native and free-ranging species, serve as buffers against urban encroachment, and offer critical ecosystem services such as carbon sequestration, temperature moderation, and stormwater management. As Godoi et al. [24] emphasize, urban green spaces also contribute to psychological well-being, recreational access, and environmental education, making them indispensable components of sustainable urban planning. Within zoos, these green areas foster both conservation outcomes and public engagement, reinforcing the interconnected mission of biodiversity protection and societal benefit. This regulation has had significant ecological benefits, particularly in urban areas, where zoos have become important refuges for free-ranging and often endemic wildlife. These green spaces support the conservation of small mammals, birds, reptiles, and invertebrates that might otherwise be displaced due to urban development. In densely populated cities, these green areas not only enhance biodiversity but also provide vital ecosystem services such as microclimate regulation, carbon sequestration, and public recreation [37, 40].

To further this urban ecological function, the CZA has also envisioned zoos as "green lungs" for polluted environments and recommends that zoos extend technical support to local governments to establish nature parks in peri-urban areas, particularly near large cities—thereby expanding ecological networks and public access to nature [12, 69].

A unique example is the National Zoological Park in Delhi, which, apart from its biodiversity role, also contributes to the preservation of national heritage monuments such as the 16th-century Purana Qila fort located adjacent to the zoo. This highlights the multifunctional conservation role that Indian zoos can play—preserving both natural and cultural heritage [69].

A strategic inflection in this model was introduced through the "Vision Plan for Indian Zoos (2021–2031)"**,** which proposed the concept of Participatory Zoos. This framework reimagines zoos not only as conservation centers but also as community-oriented biodiversity institutions [69]. By embedding local stakeholders, academic institutions, non-governmental organizations, and traditional knowledge holders into zoo-based conservation programs, the CZA advances a participatory governance model aligned with Target 13 of the GBF, which emphasizes equitable benefit-sharing and inclusive biodiversity conservation [11, 69].

In recent years, the Central Zoo Authority (CZA) has increasingly emphasized sustainable practices within Indian zoos, mandating the adoption of eco-friendly infrastructure to minimize ecological footprints and promote climate resilience. Zoos are now required to incorporate renewable energy solutions such as rooftop solar panels, battery-operated and solar-powered visitor carts, and energy-efficient lighting systems. Moreover, integrated solid waste management systems—including composting organic waste, banning single-use plastics, and ensuring proper disposal of biomedical waste—have become essential components of zoo infrastructure [10, 12, 69]. These initiatives contribute directly to the objectives of the Kunming–Montreal Global Biodiversity Framework (GBF), particularly Target 12, which promotes green infrastructure and nature-positive urban development, and Target 19, which calls for increased financial and technical support to implement biodiversity-positive interventions. By reducing their carbon emissions, managing waste responsibly, and creating awareness through model practices, zoos play a vital role not only in wildlife conservation but also in showcasing sustainable, low-impact development within urban environments.

In parallel, the CZA has made biodiversity education a core mandate, deploying outreach and interpretation programs, developing school-aligned curricula, and improving visitor engagement. These actions respond to Target 16 of the GBF, which calls for transformative action through awareness and behavioral change [16, 48].

4 Objectives and research questions

This study's objectives and hypotheses are grounded in empirical and theoretical frameworks that align Indian zoos' operational and conservation practices with the Kunming-Montreal Global Biodiversity Framework (GBF). Drawing on prior research, urban biodiversity studies emphasize the role of green spaces in mitigating habitat fragmentation [5, 17],supporting the hypothesis that larger zoos may encompass more designated green areas in alignment with Target 12 of the GBF. Similarly, evidence linking zoo size to captive species diversity [39, 58] and successful Indian Conservation breeding programs [30, 55] underpins hypotheses for Targets 4 and 13. For free-ranging biodiversity (Target 3), studies on urban green spaces as micro-habitats inform the focus on zoo green areas [21]. Climate resilience (Target 8) hypotheses derive from research on plant diversity's role in carbon sequestration [6]. Finally, the evaluation of education programs (Target 20) builds on zoos' documented capacity to foster public awareness [48]. Table 1 synthesizes these objectives, questions, and hypotheses, providing a cohesive roadmap to assess zoos' contributions to GBF targets.

5 Classification of zoos

As per the Recognition of Zoo Rules, 1992, zoos in India are classified into four categories—Large, Medium, Small, and Mini—based on parameters such as total area, annual footfall, number of species and individual animals, and the inclusion of endangered species in their collection (see Table 2). This classification framework is intended to set uniform standards for the recognition, regulation, and performance evaluation of zoos. It ensures that each institution is assessed and managed in alignment with its scale, resources, and potential contribution to conservation goals [11].

Table 1 Research objectives, questions, hypotheses

GBF target	Zoo alignment	Research question	Hypothesis
Target 2: Restore 30% of degraded terrestrial, inland water, and marine ecosystems by 2030 to enhance biodiversity, ecosystem functions, ecological integrity, and connectivity **Target 13:** Ensure fair and equitable sharing of benefits from the use of genetic resources and digital sequence information, and increase benefit-sharing by 2030	Conservation breeding programs include habitat restoration and reintroduction strategies, linking ex situ efforts with in situ recovery plans.Additionally, zoos serve as genetic resource banks through structured breeding, genetic data management, and partnerships that support equitable access and benefit-sharing	Are conservation breeding programs effective in maintaining species diversity?	H_0: Conservation breeding does not significantly protect threatened species H_1: Zoos with conservation breeding programs have a higher proportion of threatened species under protection
Target 3: Ensure that at least 30% of land, inland water, and sea areas are conserved through effective systems to safeguard biodiversity	Zoo green spaces act as microhabitats for free-ranging biodiversity, especially birds, small mammals, and invertebrates, contributing to urban conservation	Do zoos with more green areas support higher free-ranging biodiversity?	H_0: Green space does not impact free-ranging species H_1: Zoos with larger green areas have more free-ranging biodiversity
Target 4: Halt human-induced extinction and ensure recovery and conservation of threatened species. **Target 13:** Ensure fair and equitable sharing of benefits from genetic resources and digital sequence information	Larger zoos with more resources support diverse captive populations and contribute to species recovery and genetic diversity through structured breeding and data-sharing	Do larger zoos host more captive species and individuals?	H_0: Zoo size does not influence captive species counts H_1: Larger zoos have higher captive species diversity
Target 8: Increase native plant diversity and green infrastructure to enhance ecosystem resilience and climate adaptation	Zoos with designated green zones support native plant diversity, contributing to climate resilience and ecological integrity	Do zoos with more designated green zones have higher plant species diversity?	H_0: Green areas do not influence plant diversity H_1: Zoos with more green space support higher plant species diversity
Target 12: Integrate biodiversity into urban planning and increase access to green spaces for urban populations	Larger zoos contribute to urban biodiversity through green space preservation and habitat provisioning	Do larger zoos have more designated green spaces, supporting urban biodiversity?	H_0: No significant relationship between zoo size and designated green areas H_1: Larger zoos have more designated green spaces
Target 16: Enhance biodiversity awareness, education, and access to information	Zoos serve as public education hubs, using visitation and outreach programs to promote biodiversity literacy	Do zoos with higher visitation rates drive biodiversity awareness through conservation programs?	H_0: There is no association between visitation rates and conservation awareness H_1: Zoos with higher visitation have more effective biodiversity education programs

To qualify under a specific category, a zoo must meet at least four of the listed criteria, including both the number of species and the total number of animals. This system ensures consistency in the evaluation and regulation of zoos across India [26].

6 List of zoos selected

This study examines a sample of 23 zoos recognized by the Central Zoo Authority (CZA) to evaluate their contributions to the Kunming-Montreal Global Biodiversity Framework (GBF). These institutions are listed in Table 3 and mapped across India's biogeographic zones in Fig. 1. All selected facilities comply with the *Recognition of Zoo Rules*

Table 2 Categorization of zoos prescribed by central zoo authority

S. No.	Category of zoo	Criteria for qualifying to the category					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Area of the zoo (hectares)	**No. of visitors in a year (in lakhs)**	**No. of species**	**No. of animals**	**No. of endangered species**	**No. of animals of endangered species**
1	Large	75	7.5	75	750	20	100
2	Medium	35	3.5	35	350	10	50
3	Small	10	1	10	100	3	15
4	Mini	Less than 10	less than 1.00	Less than 10	Less than 100	–	–

(2009), which outline standards for animal welfare, staffing, infrastructure, and conservation responsibilities.

The selection was guided by a stratified sampling approach designed to capture ecological, institutional, and spatial diversity across India's zoo network. Out of 156 recognized zoos, our sample includes proportional representation from each category, 9 large, 8 medium, 3 small, and 3 mini zoos, ensuring coverage across the full spectrum of operational scales and capacities (Table 3).

7 Methodology

7.1 Data collection

The covariates used in this study were selected to evaluate the alignment of Indian zoos with specific targets of the Kunming-Montreal Global Biodiversity Framework (GBF) (Table 4). Each covariate reflects a measurable aspect of zoo infrastructure, biodiversity holdings, conservation breeding efforts, or public engagement.

Data for all covariates were compiled from the Annual Reports and Master Plans of zoos available on the CZA website, as of March 20, 2025. For each zoo, the most recent Annual Report was used. These documents are submitted annually under the *Recognition of Zoo Rules (2009)* and follow standardized formats prescribed by the CZA.

Institutional attributes such as Name of the Zoo, Year of Establishment, Size (Hectare), and Category were extracted directly from Master Plans and CZA recognition records. Annual Visitors data was obtained from ticketing and entry logs reported in Annual Reports. Designated Green Area (Hectare) and Plant Species counts were sourced from land-use maps and botanical inventories included in Master Plans.

Captive species and individual counts across mammals, birds, and reptiles were recorded through standardized inventory logs maintained by each zoo and submitted to the CZA. These figures reflect the zoo's ex situ conservation holdings and are updated annually. Free-ranging species (mammals, aves, reptiles) were reported by zoos based on direct field observations, camera trap data, and collaborative biodiversity surveys with forest departments or research institutions. While the CZA provides general guidelines for biodiversity documentation, there is no universally prescribed method for recording free-ranging species. As such, reporting practices vary across institutions and are largely self-reported an acknowledged limitation in the study.

Conservation Breeding Program (CBP) data, including the number of species, individuals, and threatened taxa under breeding, were obtained from official CBP records maintained by Coordinating and Participating Zoos. These records are reviewed and

Table 3 List of zoos selected for this study

S No.	Name of the zoo	Location	Year of establishment	Operator	Category
1	Alipore Zoological Garden	Kolkata, West Bengal	**1875**	State Government (Forest Department)	Medium
2	Sri Chamarajendra Zoological Garden	Mysuru, Karnataka	**1892**	State Government (Forest Department)	Large
3	National Zoological Park	New Delhi	**1959**	Ministry of Environment, Forests and Climate Change, Government of India	Large
4	Nandankanan Zoological Park	Bhubaneshwar, Odisha	**1960**	Government of Odisha, Forests and Environment Department	Large
5	Assam State Zoo cum Botanical Garden	Guwahati, Assam	**1972**	State Government (Forest Department)	Large
6	Sanjay Gandhi Biological Park	Patna, Bihar	**1972**	Department of Environment and Forests, Government of Bihar	Large
7	Sepahijala Zoological Park	Agartala, Tripura	**1972**	State Government (Forest Department)	Medium
8	Kamla Nehru Prani Sangrahalaya	Indore, Madhya Pradesh	**1974**	Indore Municipal Corporation	Medium
9	Mahendra Chaudhury Zoological Park	Chhatbir, Punjab	**1977**	State Government (Forest Department)	Large
10	Biological Park, Itanagar	Arunachal Pradesh	**1987**	Department of Environment and Forests, Government of Arunachal Pradesh	Small
11	Jawaharlal Nehru Biological Park	Bokaro, Jharkhand	**1989**	Steel Authority of India Limited (SAIL)	Medium
12	Sri Venkateshwara Zoological Park	Tirupati, Andhra Pradesh	**1993**	State Government (Forest Department)	Large
13	Tata Steel Zoological Park	Jamshedpur, Jharkhand	**1994**	Tata Steel Zoological Society	Medium
14	Dhauladhar Nature Park	Palampur, Himachal Pradesh	**1992**	State Government (Forest Department)	Small
15	Arignar Anna Zoological Park	Vandalur, Tamil Nadu	**1985**	State Government (Forest Department)	Large
16	Rajiv Gandhi Zoological Park	Pune, Maharashtra	**1999**	Pune Municipal Corporation	Medium
17	Pilikula Biological Park	Mangaluru, Karnataka	**2001**	Dr. Shivaram Karanth Pilikula Nisarga Dhama Society	Large
18	Shyama Prasad Mukherjee Zoological Garden	Surat, Gujarat	**2003**	Municipal Corporation of Surat	Medium
19	Biological Park Chidiyatapu	Andaman and Nicobar Islands	**2009**	State Government (Forest Department)	Small
20	Lion Breeding Centre and Multiple Safari Park	Etawah, Uttar Pradesh	**2013**	State Government (Forest Department)	Mini
21	Zoological Park and Rescue Centre	Gorewada, Maharashtra	**2015**	State Government (Forest Department)	Mini
22	Nandan Van Zoo and Safari	Naya Raipur, Chhattisgarh	**2016**	State Government (Forest Department)	Medium
23	Greens Zoological, Rescue and Rehabilitation Centre	Jamnagar, Gujarat	**2019**	Greens Zoological, Rescue and Rehabilitation Centre Society	Mini

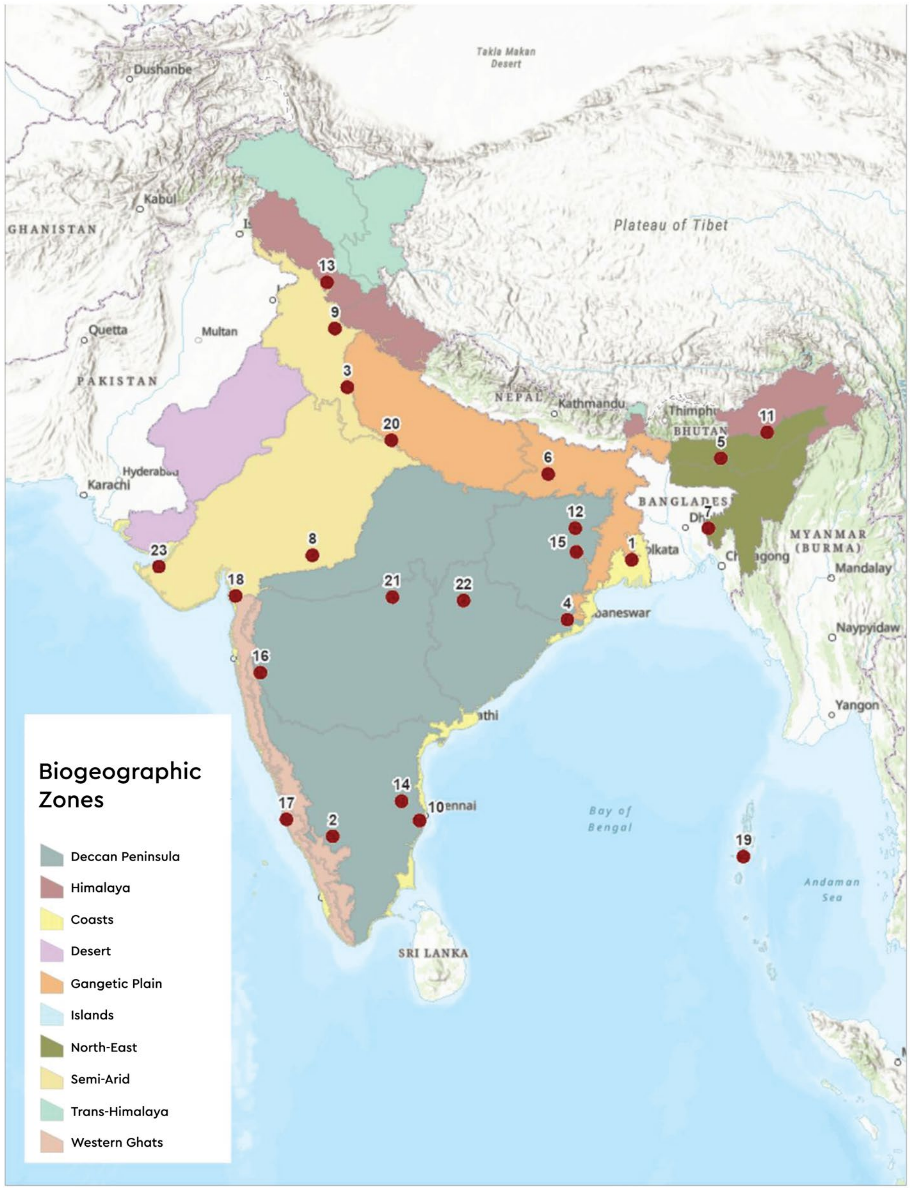

Fig. 1 Spatial overlay of zoos on the biogeographic zones map of India. Zoo locations are numbered corresponding to the entries in Table 2

approved by the CZA and reflect the zoo's contribution to national species recovery efforts.

7.2 Methodological limitations

While the study design is comprehensive, several limitations are noted:

- **Data consistency**: Not all zoos maintain complete or uniformly detailed records, especially for free-ranging species and plant inventories.
- **Cross-sectional scope**: The study captures a single point in time and does not account for temporal changes in zoo operations or biodiversity outcomes.

Table 4 Covariates analyzed in the study—operational and biodiversity metrics of CZA-recognized zoos

Covariate	Description
Name of the zoo	The official name of the zoo as recognized by the Central Zoo Authority (CZA)
Year of establishment	The year in which the zoo was founded or officially opened
Size (hectare)	The total land area of the zoo measured in hectares, as per the Master Plan approved by CZA
Category	The classification of the zoo as per CZA guidelines (e.g., large, medium, small, rescue center)
Annual visitors	The number of visitors the zoo receives annually, based on reported data
Designated green area (hectare)	The area designated by the zoo for green cover, including forests, gardens, and plantations, measured in hectares
Plant species	The number of different plant species found within the zoo
Captive mammal species	The number of mammal species housed in captivity at the zoo
Captive mammal numbers	The total number of individual mammals in captivity
Captive Aves species	The number of bird species housed in captivity at the zoo
Captive Aves numbers	The total number of individual birds in captivity
Captive reptile species	The number of reptile species housed in captivity at the zoo
Captive reptile numbers	The total number of individual reptiles in captivity
Free-ranging mammal species	The number of wild mammal species that naturally occur within the zoo premises
Free-ranging Aves species	The number of wild bird species that naturally occur within the zoo premises
Free-ranging reptile species	The number of wild reptile species that naturally occur within the zoo premises
Conservation breeding program species	The list of animal species that the zoo is breeding as part of a CZA-approved Conservation Breeding Program
Number of captive threatened mammal species	The number of mammal species in captivity that are classified as threatened
Number of captive threatened Aves species	The number of bird species in captivity that are classified as threatened
Number of captive threatened reptile species	The number of reptile species in captivity that are classified as threatened
Conservation breeding program species	The total number of species under the zoo's Conservation Breeding Program
Conservation breeding program individuals	The total number of individuals bred under the zoo's Conservation Breeding Program
Threatened conservation breeding program species	The number of threatened species included in the Conservation Breeding Program

Despite these limitations, the selected covariates and data sources provide a robust foundation for evaluating the strategic role of Indian zoos in advancing national and global biodiversity goals (Table 4).

The shapefile for the Biogeographic regions of India was downloaded from India Biodiversity Portal (https://indiabiodiversity.org/user/download-logs?offset=16&sourceType=Map), (India Biogeographic Zones, created on 13-4-2025, assessed on 15th April 2025). We used the ArcGIS online Map Viewer to create the map.

The statistical analyses for this study were conducted using R Studio 4.3.3 [47].

8 Analysis

8.1 Target 2 and 13: zoo conservation efforts and policy implications

To evaluate the effectiveness of Conservation Breeding Programs, in maintaining species diversity, a chi-square test was conducted to assess the association between the presence of 'Conservation Breeding Program Species' and the proportion of 'Number of

Captive Threatened Mammal Species', 'Number of Captive Threatened Aves Species', and 'Number of Captive Threatened Reptile Species' under protection in zoos. The dataset included multiple zoos, each with varying numbers of 'Captive Threatened Species' and 'Conservation Breeding Program Species'. A contingency table was constructed comparing the number of 'Threatened Conservation Breeding Program Species' to the total number of 'Captive Threatened Species' across all zoos. The chi-square test was applied to determine whether the observed distribution significantly deviates from expected values under the assumption that Conservation Breeding Program have no effect on species protection.

8.2 Target 3: free-ranging biodiversity in zoos

To evaluate whether 'Designated Green Area (Hectare)' influences 'Free-Ranging Mammal Species', 'Free-Ranging Aves Species', and 'Free-Ranging Reptile Species', we conducted a Pearson correlation analysis and a multiple linear regression model. Pearson correlation was used to assess the relationship between 'Designated Green Area (Hectare)' and the total count of 'Free-Ranging Mammal Species', 'Free-Ranging Aves Species', and 'Free-Ranging Reptile Species'. A multiple linear regression model was performed with 'Free-Ranging Mammal Species', 'Free-Ranging Aves Species', and 'Free-Ranging Reptile Species' as the dependent variables, while 'Designated Green Area (Hectare)' and 'Size (Hectare)' were included as independent variables.

8.3 Target 4 and 13: zoos & captive species conservation

To investigate the relationship between zoo size ('Size (Hectare)') and the number of captive species ('Captive Mammal Species' + 'Captive Aves Species' + 'Captive Reptile Species'), we performed a Pearson correlation analysis using zoo size ('Size (Hectare)') and the total number of captive species. Additionally, a one-way ANOVA was conducted to determine whether captive species numbers significantly differed across different zoo categories ('Category'). The Pearson correlation test assessed the strength and direction of the relationship, while the ANOVA helped identify whether differences in captive species counts were statistically significant among zoo categories. Post-hoc Tukey's HSD tests were applied to further examine pairwise differences.

8.4 Target 8: climate resilience and plant diversity

To investigate whether zoos with larger designated green areas support higher plant species diversity, we conducted two statistical tests. First, a Spearman's rank correlation test was performed to assess the relationship between 'Designated Green Area (Hectare)' and 'Plant Species'. Since the normality tests (Shapiro–Wilk) indicated that the data was not normally distributed, a non-parametric correlation test was chosen. Additionally, a Kruskal–Wallis test, a non-parametric alternative to ANOVA, was conducted to examine differences in 'Plant Species' diversity across different zoo categories.

8.5 Target 12: urban biodiversity and green spaces

To investigate whether larger zoos allocate more space for urban biodiversity conservation, the relationship between zoo size ('Size (Hectare)') and green cover ('Designated Green Area (Hectare)') was analyzed. A Shapiro–Wilk normality test was conducted to assess the distribution of both variables. Based on the outcome of the normality test, a

Spearman's rank correlation was selected to evaluate the association between zoo size and designated green areas. Additionally, a linear regression analysis was performed to quantify the strength and direction of this relationship.

8.6 Target 16: public education and awareness

To investigate whether zoos with higher visitation rates drive biodiversity awareness through conservation programs, we conducted both a Spearman's rank correlation test and a linear regression analysis using the number of 'Annual Visitors' and total captive species ('Captive Mammal Species', 'Captive Aves Species', and 'Captive Reptile Species') as a proxy for participation in education programs.

9 Results

9.1 Target 2 and 13: zoo conservation efforts and policy implications

The chi-square test revealed a statistically significant association between the presence of conservation breeding programs and the number of threatened species housed in zoos ($\chi2 = 7.35$, $df = 1$, $p = 0.0067$). Zoos participating in conservation breeding programs were found to host a disproportionately higher number of threatened species compared to those without such programs. This suggests that conservation breeding initiatives are positively linked to the protection and maintenance of threatened taxa within ex situ facilities. Figure 2 depicts this association, with zoos involved in breeding programs showing consistently higher counts of captive threatened species. These findings highlight the potential of targeted breeding programs to contribute to species recovery goals under the Global Biodiversity Framework.

9.2 Target 3: free-ranging biodiversity in zoos

Pearson correlation analysis indicated a moderate positive relationship between 'Designated Green Area (Hectare)' and both 'Free-Ranging Mammal Species' ($r = 0.51$, $p = 0.030$) and 'Free-Ranging Aves Species' ($r = 0.47$, $p = 0.048$), suggesting that larger

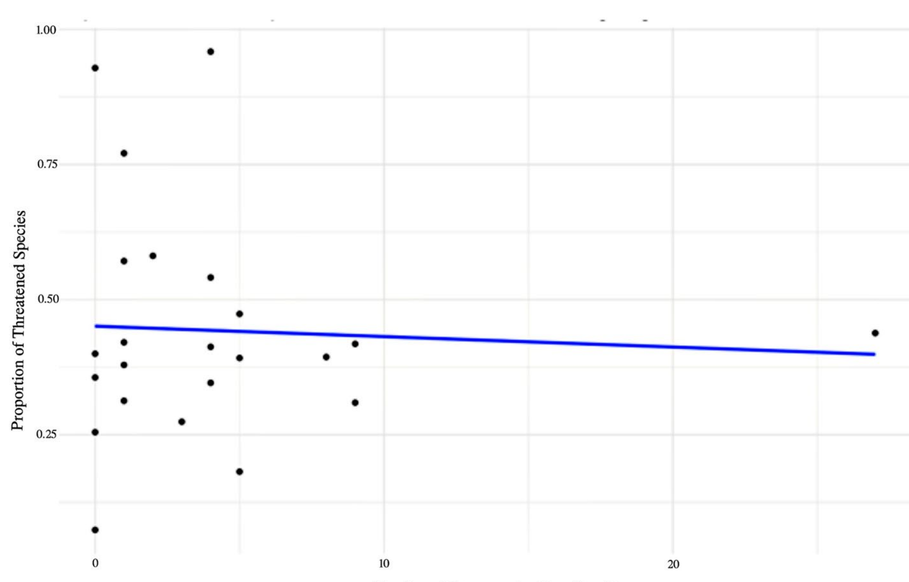

Fig. 2 Association between conservation breeding programs and number of captive threatened species in Indian zoos

green areas are significantly associated with greater mammal and bird diversity. In contrast, the correlation for reptiles was negligible and not statistically significant ($r = 0.05$, $p = 0.845$), implying minimal influence of green area on reptile presence. These findings were further supported by multiple linear regression models. For mammals, designated green area had a significant positive effect (Estimate = 0.02097, $p = 0.036$), with an adjusted R2 of 0.18. Similarly, for birds, green area was a significant predictor (Estimate = 0.2048, $p = 0.032$), with an adjusted R2 of 0.176. However, reptile models showed no significant predictors, with a negative adjusted R2 (– 0.047), indicating poor model fit.

Figure 3 illustrates these patterns, with scatter plots and fitted regression lines demonstrating a clear upward trend for mammals and birds. The narrow confidence intervals and clustering of data points around the line further underscore the positive association between designated green space and free-ranging species richness in zoos.

9.3 Target 4 and 13: zoos and captive species conservation

The Pearson correlation test indicated a weak positive correlation (r = 0.244r) between zoo size and the number of captive species; however, this correlation was not statistically significant ($p = 0.261$ *pp*). The 95% confidence interval ranged from – 0.187 to 0.597, suggesting considerable uncertainty in the relationship between these variables (Fig. 4).

ANOVA results indicated a statistically significant difference in captive species counts across zoo categories ($F(4,18) = 3.43$, $p = 0.0299$). However, post-hoc analysis using Tukey's HSD test revealed that none of the pairwise comparisons between zoo categories were statistically significant at the 0.05 level. For instance, the difference between medium and large zoos was not significant ($p = 0.201$), and similar patterns were observed across other category comparisons Fig. 5.

These findings suggest that while there is some variation in species counts across zoo types, zoo category alone may not be a strong predictor of captive species diversity. The absence of significant pairwise differences, despite an overall significant ANOVA result, points to a complex relationship possibly influenced by additional variables such as

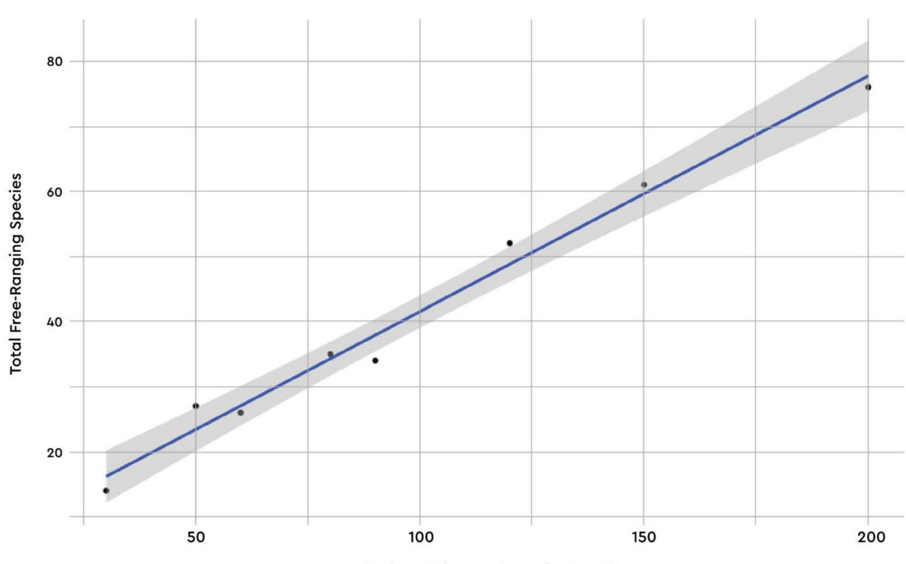

Fig. 3 Impact of green area on free-ranging species

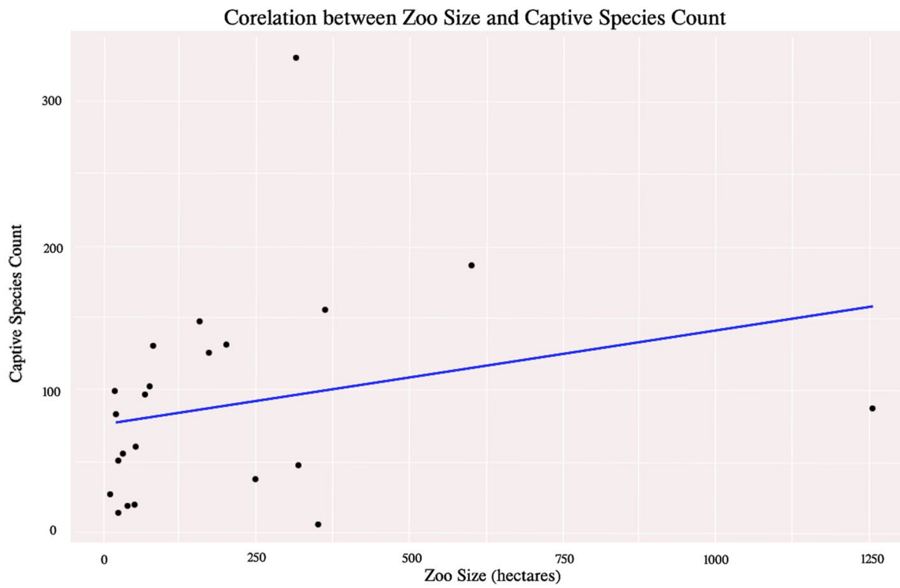

Fig. 4 Correlation between zoo size and captive species count

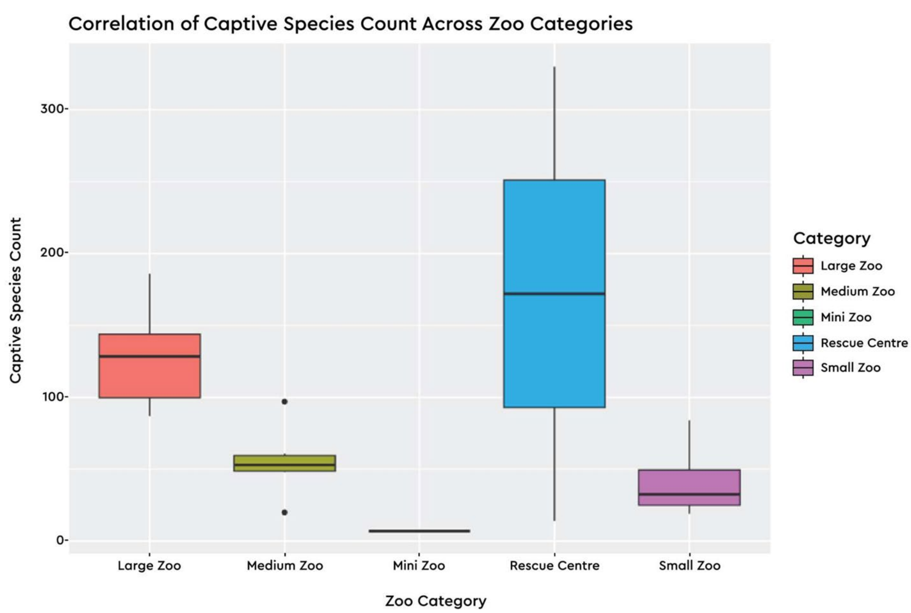

Fig. 5 Comparison of captive species count across zoo categories

institutional priorities, conservation mandates, habitat design, and funding structures. Further investigation is warranted to explore these underlying factors and their roles in shaping species composition within captive facilities.

9.4 Target 8: climate resilience and plant diversity

The Spearman's correlation test yielded a weak, non-significant negative association between designated green area and plant species diversity ($\rho = -0.1828$, $p = 0.5143$), suggesting that larger green spaces do not correspond to increased plant richness in zoos. Similarly, the Kruskal–Wallis test revealed no significant differences in plant species diversity across zoo categories ($\chi 2 = 4.2167$, df = 4, $p = 0.3775$). These findings were further supported by the boxplot visualization (Fig. 6), which showed no discernible trend in plant diversity among different zoo categories, indicating that neither green area size nor zoo classification significantly influences plant species richness. This challenges the assumption that larger green zones inherently promote higher plant diversity within zoos. Several factors could contribute to this outcome, including variations in habitat management practices, the selection of plant species, and differences in climate conditions across zoos.

9.5 Target 12: urban biodiversity and green spaces

The Spearman's correlation test revealed a moderate positive correlation between zoo size and designated green areas (rho = 0.6078, $p = 0.0087$), indicating that larger zoos tend to allocate more land for green spaces. The linear regression analysis further supported this relationship, with a statistically significant positive slope (Estimate = 0.2586, $p = 0.0407$), suggesting that an increase in zoo size is associated with an increase in designated green areas. However, the R^2 value of 0.2366 suggests that only 23.66% of the variance in designated green areas is explained by zoo size, highlighting the influence of other factors.

The positive trend in the data points seen in Fig 7 suggests that larger zoos tend to have more green space, aligning with the correlation and regression results. The regression line, fitted using a linear model, indicates a moderate positive association, meaning that as zoo size increases, the amount of land designated for green spaces also tends to increase. However, the spread of data points around the regression line suggests some variability, indicating that factors other than zoo size may also influence green space allocation. The presence of outliers or widely dispersed points further supports the need for additional investigation into other influencing variables.

The findings indicate that zoo size is positively correlated with the allocation of designated green areas, supporting the hypothesis that larger zoos are more likely to allocate space for urban biodiversity conservation. However, the relatively low R2 value suggests

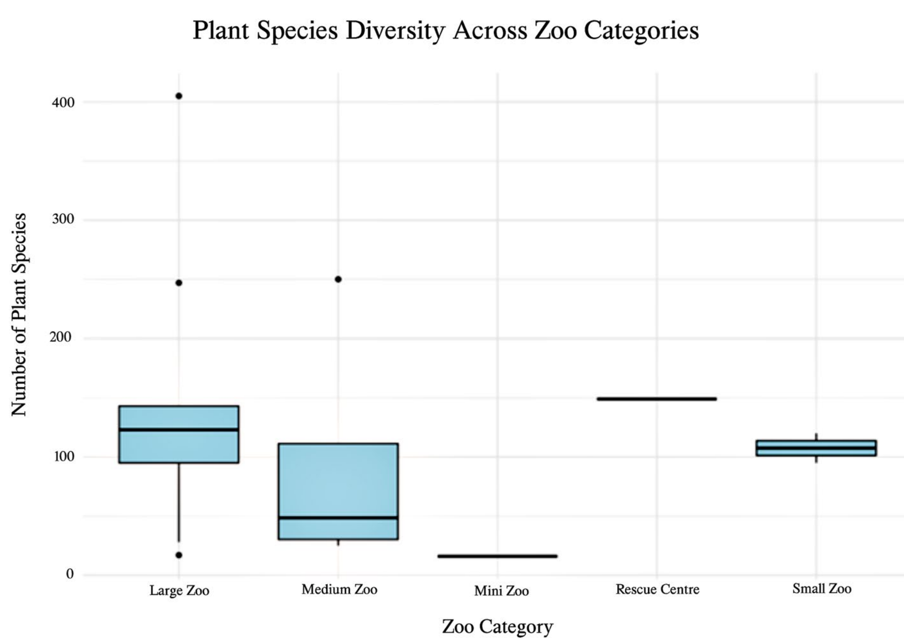

Fig. 6 Plant species diversity across zoo categories

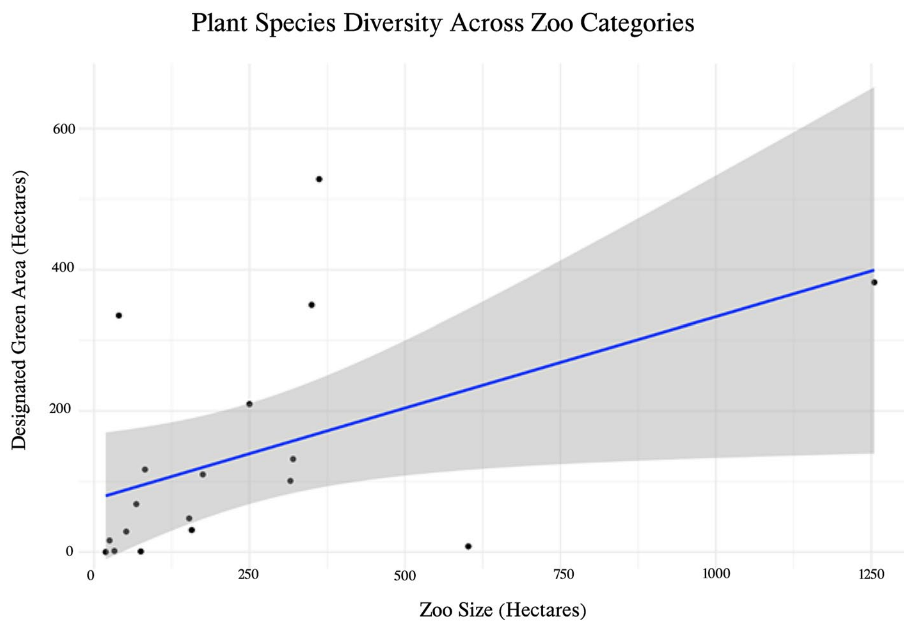

Fig. 7 Relationship between zoo size and green spaces

that zoo size alone accounts for only a portion of the variability in green space allocation. This indicates that additional factors—such as funding availability, conservation policies, and zoo management strategies—may play a significant role in determining the amount of green space dedicated to biodiversity conservation. The results suggest that while zoo size is an important factor, it is not the sole determinant of green space allocation.

9.6 Target 16: public education and awareness

The Spearman's rank correlation test revealed a moderate positive correlation between annual visitors and education program participation ($\rho = 0.423$, $p = 0.0498$), indicating a statistically significant, though weak, relationship. This suggests that zoos with higher visitor engagement tend to have richer captive biodiversity, which may contribute to educational outreach efforts. However, a linear regression analysis performed to further evaluate the relationship between annual visitors and education program participation showed a small positive effect, with the coefficient for annual visitors being 1.436×10^{-5} ($p = 0.305$), which was not statistically significant. The model's multiple R-squared value of 0.0523 indicates that annual visitor numbers account for only a small proportion (5.23%) of the variation in education program participation, suggesting that other factors may be more influential in determining participation rates.

The scatter plot (Fig. 8) demonstrates the relationship between annual visitors and education program participation. While an upward trend is observable, the distribution of data points indicates a high degree of variability, with several outliers present. The fitted regression line shows a weak positive slope, further supporting the weak correlation. The presence of outliers suggests that additional unmeasured variables, such as zoo size, funding, or conservation priorities, could influence the effectiveness of biodiversity education programs. These findings suggest that while there is some relationship between visitor numbers and education program participation, it is not strong enough to be considered a primary driver, highlighting the need to consider other factors in future research.

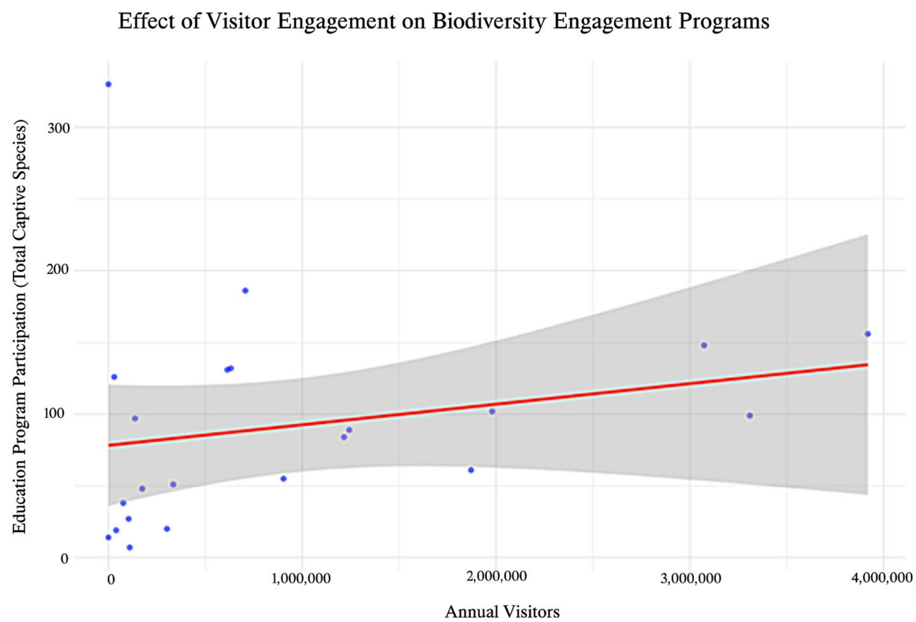

Fig. 8 Effect of visitor engagement on biodiversity education programs

10 Discussion

The results reveal a statistically significant association between the presence of conservation breeding programs in Indian zoos and the protection of threatened species. This supports the hypothesis that zoos prioritizing ex situ conservation efforts play a critical role in safeguarding biodiversity, particularly for species facing extinction due to habitat fragmentation and other anthropogenic pressures [15]. For instance, Indian zoos such as the Arignar Anna Zoological Park (Tamil Nadu) and Nandankanan Zoological Park (Odisha) have successfully bred and maintained populations of the critically endangered gharial (*Gavialis gangeticus*) and the vulnerable Indian rhinoceros (*Rhinoceros unicornis*), aligning with global frameworks like the Kunming-Montreal Global Biodiversity Framework (GBF) **Target 2** (Arignar Anna Zoological [1, 2, 16, 46]. These programs not only prevent species extinctions but also provide genetically viable populations for future reintroductions, as demonstrated by the successful reintroduction of the pygmy hog (*Porcula salvania*) in Assam [41] and tiger (*Panthera tigris tigris*) reinforcement efforts involving hand-reared individuals and *in-situ* supplementation of orphaned cubs, which achieved high survival rates (72–100%) and reproductive success (50–75% of tigresses breeding post-release) [46].

Several captive-bred individuals have now been successfully released into the wild, contributing to ecosystem functioning as prey species and seed dispersers. This illustrates the importance of long-term, scientifically managed breeding programs for species with poorly understood ecology and reproductive behavior [32, 50].

These efforts collectively advance Target 4 of the GBF, which emphasizes the conservation of genetic diversity and recovery of wild populations. However, long-term success across all these programs hinges on parallel investments in habitat restoration, threat mitigation, and post-release monitoring to ensure population viability and ecological integration [52].

The success of these programs must be contextualized within broader challenges. While Indian zoos report higher proportions of threatened species under protection, genetic bottlenecks in captive populations—observed in the Asiatic lion (*Panthera leo persica*) breeding program at Sakkarbaug Zoo, Gujarat remain a concern due to small founder populations and limited gene flow [15, 33]. Nevertheless, Sakkarbaug Zoo has pioneered meticulous pedigree management and regional stud-book coordination, facilitating occasional transfers with other centers to bolster genetic diversity across its lion cohorts. The Greens Zoological, Rescue and Rehabilitation Centre as a participatory zoo under the Conservation Breeding Programme has actively bred the Asiatic lions with dual aim of preserving the genetic diversity and preparing individual for potential reintroduction in the wild (GZRRC, 2024). To address these gaps, the Central Zoo Authority (CZA) mandates standardized genetic audits and prioritizes species based on IUCN Red List criteria [52], a policy approach that mirrors the GBF's call for equitable conservation action. These findings underscore the need for integrating ex situ efforts with in situ habitat restoration [43].

For Target 13 (equitable benefit-sharing and indigenous rights), Indian zoos face dual challenges. While partnerships with tribal communities, such as the Soliga tribe in Karnataka, integrate traditional ecological knowledge into conservation (e.g., sacred grove preservation for the Indian giant squirrel, *Ratufa indica*), policy shifts like the Forest (Conservation) Amendment Act (2023) risk marginalizing indigenous groups by prioritizing commercial ecotourism and protected area expansions, as seen in the Kumbalgarh (leopard, *Panthera pardus*) and Nauradehi sanctuaries [60]. Balancing conservation with FPIC (Free, Prior, and Informed Consent) principles and inclusive co-management models calls for the formulation of comprehensive policies that integrate traditional ecological knowledge with modern scientific approaches, ensuring that the rights and interests of indigenous communities are duly recognized and protected [48].

Our results demonstrated a moderate positive correlation between designated green-area size and both mammal and bird richness, closely mirroring the classic species–area relationship observed in urban parks [5, 57]. In particular, Sorace [57] found that park size overrides isolation effects in determining vertebrate species richness, underscoring the primacy of area in shaping bird and mammal communities. Our multiple regression analyses further confirmed that designated green area is a significant predictor of free-ranging mammal and bird presence, although these models accounted for only ~ 18% of variance—suggesting that additional factors such as vegetation structure and landscape connectivity also play important roles [57].

In stark contrast, reptile richness showed no meaningful association with green-area size non-significant regression coefficient), a pattern consistent [19], Delaney and team reported that reptile diversity in urban landscapes is governed more by microhabitat features and fragmentation than by patch area per se, with even small "microreserves" supporting substantial reptile assemblages when critical thermal and substrate conditions are present. This taxon-specific response indicates that, while enlarging green spaces within zoo grounds can effectively bolster mammal and bird diversity, reptile conservation will require targeted enhancements of microhabitat complexity—such as the creation of thermal refugia, coarse woody debris, and habitat corridors—to meet their specialized ecological requirements.

By expanding designated green areas, zoos are directly contributing to the achievement of Target 3 of the Kunming–Montreal Global Biodiversity Framework—which mandates effective conservation of at least 30% of terrestrial and inland water areas by 2030 through well-connected, ecologically representative protected areas and other effective area-based conservation measures [16]. However, our findings highlight that realizing similar biodiversity gains for reptiles will necessitate more nuanced habitat design and connectivity interventions beyond simple increases in patch area.

These results indicate that zoo size alone does not reliably predict captive species richness. Under Target 4—which mandates urgent management actions to halt species extinctions and maintain genetic diversity through both *in situ* and *ex situ* conservation—our findings imply that facility scale is insufficient; zoos must implement robust genetic stewardship, demographic monitoring, and prioritization of threatened taxa to meet their conservation obligations [16]. Rather than size, factors such as funding streams and institutional priorities appear to drive captive species diversity. For example, public sponsorship—a key revenue source for zoo conservation programs—is influenced more by species appeal and donor motivations than by zoo category, affecting how institutions allocate resources for species acquisition and breeding [20]. Moreover, coordinated *ex situ* initiatives like the EAZA ex situ Programme demonstrate that strategic population management, studbook analyses, and inter-zoo collaboration can sustain genetically healthy populations across hundreds of species, irrespective of individual zoo size [64].

The finding that green space extent and zoo category don't predict plant diversity suggests that zoos are not fully leveraging their green areas for nature-based solutions, as envisioned by Target 8 of the Kunming-Montreal Global Biodiversity Framework (GBF). This target focuses on minimizing climate change impacts and building ecosystem resilience through nature-based and ecosystem-based approaches. While zoos can contribute to conservation efforts, their green areas need to be managed more effectively to maximize their potential for biodiversity and resilience [23].

As Seddon et al. emphasize, NbS must be rigorously designed, monitored, and tailored to deliver biodiversity and climate co-benefits, rather than relying on area alone. Zoos, with their horticultural expertise and living collections, are uniquely positioned to model high-value NbS by integrating multi-layered plantings, water-retention features, and climate-adapted species selection to create microhabitats that buffer temperature extremes and enhance carbon sequestration, thereby directly advancing Target 8's call for adaptation and mitigation actions [44, 53].

Urban zoos in India serve as critical green spaces, contributing significantly to biodiversity conservation, and ecosystem services within rapidly urbanizing landscapes. These institutions not only house diverse fauna but also maintain substantial vegetative cover, aiding in air purification, temperature regulation, and providing habitats for various species. The National Zoological Park in Delhi, spanning approximately 176 acres, is a prime example of an urban zoo functioning as a green oasis amidst the city's dense infrastructure. Situated between the historic Purana Qila and Humayun's Tomb, the zoo supports a variety of flora and fauna, including free-ranging species such as jackals and migratory birds like the painted stork (*Mycteria leucocephala*) [55, 63]. A study by The Energy and Resources Institute (TERI) estimated the zoo's annual ecosystem services value at INR 422.76 crore, highlighting its role in biodiversity conservation, carbon sequestration, and recreation (The Energy and Resources Institute (TERI), 2020). The total value of the one-time cost of services such as carbon storage and land value provided by the zoo is estimated to be INR 55,209.45 crore. This study highlights the importance of habitats such as zoos to human wellbeing and the need for replication across India (The Energy and Resources Institute (TERI), 2020).

The Assam State Zoo cum Botanical Garden, located within the Hengrabari Reserve Forest in Guwahati, spans 175 hectares and houses over 115 species. Its integration with the reserve forest allows for a semi-natural environment that supports both captive and local wildlife populations [36]. Similarly, the Indira Gandhi Zoological Park in Visakhapatnam, covering 625 acres within the Kambalakonda Reserve Forest, provides a habitat for approximately 850 animals across 75 species. The zoo's location amidst the Eastern Ghats enhances its role in conservation and education, attracting around 10 million visitors annually (Arignar Anna Zoological [2]).

Moreover, zoos' capacity for public engagement can amplify NbS uptake beyond their grounds. By establishing long-term monitoring plots and sharing adaptive management lessons, zoos can inform municipal and regional climate resilience strategies [44]. Campaigns such as WCS's *#FramingOurFuture*, launched at COP26 in partnership with AZA-accredited institutions, demonstrate how zoos can educate and mobilize millions to support policy measures that protect intact forests and restore coastal ecosystems—nature-based interventions that deliver one-third of the action needed to limit warming to 1.5 °C (Wildlife Conservation Society, 2021). By centering ecological design, rigorous monitoring, and public advocacy, zoos can transform their green spaces into living laboratories of NbS, fulfilling their promise as catalysts for climate-resilient biodiversity conservation under the GBF.

Zoos exhibit a moderate positive correlation between total area and green-space allocation, but zoo size explains only 23.7% of the variance in green-area extent. This mirrors urban green-infrastructure research showing that patch area alone is insufficient to deliver ecosystem services and biodiversity benefits without integrated ecological design and management [13, 66]. Moreover, institutional drivers such as funding availability, policy frameworks, and visitor engagement goals—further shape green-space allocation in zoos, indicating that to maximize conservation impact under Target 8 of the Kunming–Montreal GBF, zoos must pair land designation with strategic habitat design, dedicated conservation funding, and cross-disciplinary collaboration [3, 5].

The observed weak correlation between annual zoo visitation and participation in biodiversity education programs highlights a critical insight: merely attracting more visitors does not automatically enhance public engagement with biodiversity issues. This finding is particularly relevant to Target 16 of the Kunming–Montreal Global Biodiversity Framework (GBF), which emphasizes the importance of enabling sustainable consumption choices through improved education and access to relevant information [16].

Zoos are uniquely positioned to contribute to this target by serving as platforms for conservation education. They offer interactive exhibits, workshops, and outreach programs that promote conservation awareness among diverse audiences, including school groups, families, and tourists [48]. However, the variability in education program participation suggests that factors beyond visitor numbers—such as the quality of educational outreach, funding for conservation programs, and zoo infrastructure—play significant roles in determining the effectiveness of these programs [48].

To align more closely with Target 16, zoos should focus on enhancing the quality and reach of their educational interventions rather than relying solely on footfall as a metric for impact. Strategies such as curriculum-aligned programs for school and college students, multilingual signage and interpretation, inclusive design for accessibility, and digital outreach tools can significantly broaden the impact of biodiversity education. For instance, initiatives like the Thalir and YUVA programs by the Young Indians Climate Change Vertical in India have shown how targeted youth engagement through experiential learning can instil long-term pro-environmental behavior [45].

Furthermore, participatory platforms where local communities, schoolchildren, and visitors engage directly in conservation tasks—such as habitat restoration, enrichment design, or citizen science—can shift zoos from being passive learning spaces to active agents of behavioral change. When combined with feedback mechanisms, such efforts can improve program design, build local ownership of conservation, and align with SDG 4.7 and GBF Target 16. In this context, the role of zoos evolves beyond education toward environmental stewardship and transformative learning [28].

Additionally, many animals raised in other captive care settings cannot adapt to wild environments due to the loss of innate behaviors critical for survival [56]. Given these realities, long-term, specialized care becomes essential. However, maintaining lifetime care is both resource- and cost-intensive. It involves ongoing veterinary attention, specialized diets, species-specific enclosures, enrichment programs to prevent psychological distress, and in many cases, geriatric care facilities [28, 32, 35]. Maintaining large mammals in captivity can cost $15,000–$75,000 annually, depending on species and care needs [22]. Even in the wild, translocation is costly—up to $2,393 per animal, with tracking making up 56% of the cost [72].

11 Conclusion

India's zoos stand at a critical juncture—where traditional roles rooted in exhibition and passive learning must evolve into active, inclusive, and outcomes-driven contributions to biodiversity conservation. Under the Kunming–Montreal Global Biodiversity Framework (GBF), particularly Targets 2, 4, 16, and 19, and the Sustainable Development Goals (especially SDG 4.7), zoos have the opportunity to reframe themselves not merely as enclosures for wildlife, but as dynamic institutions of conservation science, lifelong education, community participation, and environmental stewardship.

The evidence is clear. When zoos adopt curriculum-aligned and experiential learning programs—coupled with digital, multilingual, and accessible outreach tools, they unlock transformative learning experiences for youth and the public. Participatory models that involve local communities and visitors in citizen science, habitat restoration, and enrichment tasks deepen engagement and shift perceptions, cultivating a sense of shared responsibility for nature.

At the same time, zoos serve a vital role in wildlife rescue, rehabilitation, and animal welfare, especially for animals seized from trafficking, illegal captivity, and conflict zones. However, the challenges of permanent captivity—from behavioral imprinting to chronic health conditions—demand long-term veterinary care, specialized diets, and infrastructural investments. These needs underscore the limitations of state-managed facilities alone and point to the emerging importance of public–private partnership, private-sector and CSR-backed models.

In moving forward, the success of India's zoos will hinge not on footfall or enclosure counts, but on their ability to integrate ecological design, inclusive governance, strategic partnerships, and rigorous impact assessment into their operations. It will require bold shifts—from reactive care to proactive recovery, from silos to systems, and from transactional education to transformative action. Only then can zoos truly serve as resilient, adaptive, and just institutions that embody the spirit of the GBF and help secure a biodiverse and equitable future for all.

Acknowledgements
We extend our heartfelt gratitude to Mr. Vivaan Karani and Mr. AaKash Pratap Singh, for their visionary leadership and consistent encouragement that inspired the direction of this study. The concept and development of this work were significantly shaped through frequent and insightful conversations with them. We are equally grateful to Mr. S. C. Sharma, Former Member Secretary, Central Zoo Authority; Mr. P. R. Sinha, Former Director, Wildlife Institute of India; and Mr. B. S. Bonal, Former Member Secretary, National Tiger Conservation Authority, whose rich perspectives and their inputs provided a strong foundation for this research. We also wish to thank the Greens Zoological Rescue and Rehabilitation Centre (GZRRC) and the Greens Zoological Rescue and Rehabilitation Centre Society (GZRRCS) for their unwavering support and valuable contributions. Our sincere thanks go to the Central Zoo Authority (CZA) and the Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India, for upgrading the scientific management of animals in captivity India . A special note of appreciation goes to Dr. Soumya Das Gupta for his expert guidance and constructive feedback, which greatly enriched the development of this project. The collective support from these individuals and institutions has been instrumental in the successful completion of this research.

Author contributions
Conceptualization, B.K.G. and S.D.G.; methodology, B.K.G. and S.D.G.; software, S.D.G.; validation, S.D.G. and B.K.G.; formal analysis, S.D.G.; investigation, B.K.G. and S.D.G.; resources, B.K.G, S.K.S; data curation, S.D.G.; writing—original draft preparation, B.K.G. and S.D.G.; writing—review and editing, S.D.G., B.K.G. S.K.S; visualization, B.K.G., S.K.S; supervision, B.K.G.; project administration, B.K.G.; funding acquisition, B.K.G. All authors have read and agreed to the published version of the manuscript.

Funding
This research was supported by Naturesqe.

Data availability
All data used in this study were obtained from publicly available sources, including government databases, official websites of the Central Zoo Authority of India, peer-reviewed literature, and open-access environmental datasets. No proprietary or confidential data were used. The datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 25 June 2025 / Accepted: 3 November 2025
Published online: 16 November 2025

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