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Emerging Technological Innovations and Sustainable Approaches in Modern Zoological Research

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Abstract

Modern zoological research is undergoing a major transformation driven by technological advancement and the growing need for sustainability. This paper reviews how emerging tools—including artificial intelligence, remote sensing systems, genomic techniques, and citizen science platforms—are reshaping wildlife studies and conservation practices. These technologies improve species monitoring, ecological data analysis, and biodiversity protection while reducing environmental disturbance. The study also discusses ethical considerations, challenges in implementation, and future prospects for integrating innovation with long-term ecological sustainability.

Keywords: Zoology; Artificial Intelligence; Sustainability; Genomics; Remote Sensing; Big Data; Conservation Technology

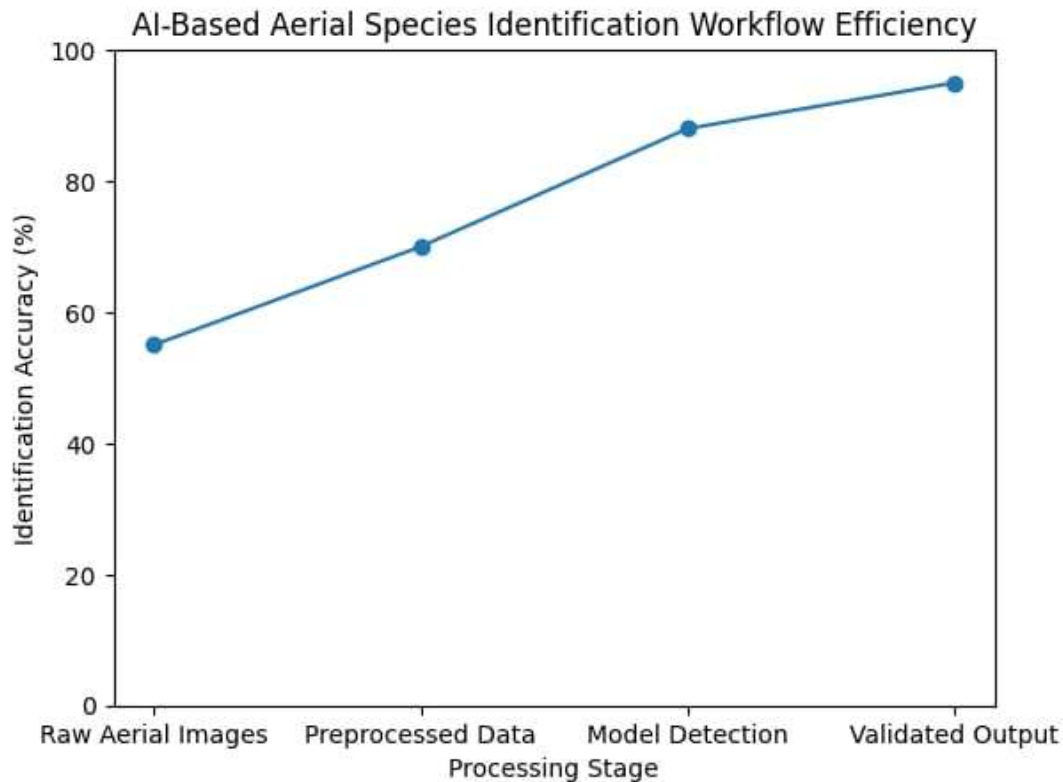
Introduction

Zoology, the branch of biology dedicated to the study of animals, has traditionally relied on direct observation, specimen collection, and field surveys. However, rapid technological progress has expanded research possibilities far beyond conventional methods. Digital tools now support large-scale data collection, automated species identification, and predictive ecological modeling. At the same time, biodiversity loss, climate change, and habitat degradation have made sustainability a central objective of zoological research. Integrating technological innovation with conservation principles is therefore essential for addressing present and future environmental challenges. This paper outlines major technological trends that contribute to sustainable progress in zoology.

Artificial Intelligence and Machine Learning in Zoology AI-Based Species Identification

Artificial intelligence (AI), particularly deep learning techniques, has become a powerful tool for analyzing camera-trap images, bioacoustic recordings, and video data. Automated identification systems reduce the time required for manual analysis and help minimize human error, making biodiversity monitoring more efficient and consistent.





- **Predictive Ecological Modeling**
Machine learning models can integrate climate variables, habitat data, and population records to forecast species distribution, extinction risk, and ecological responses to environmental change. These models support evidence-based conservation planning.
- **Limitations and Concerns**
Despite its benefits, AI application in zoology faces issues such as biased datasets, limited representation of rare species, and the need for technical expertise. Addressing these limitations is crucial for reliable outcomes.

Remote Sensing and Field Monitoring Technologies

- **Unmanned Aerial Vehicles (Drones)**
Drones equipped with optical and thermal sensors enable researchers to monitor wildlife populations and habitats with minimal disturbance. They are particularly useful in remote, dangerous, or ecologically sensitive areas.
- **Satellite Observation**
Satellite imagery provides long-term, large-scale environmental data that help track land-use changes, habitat fragmentation, and migration routes.
Satellite observation refers to the use of Earth-orbiting satellites to collect spatial and temporal data on habitats, ecosystems, and wildlife populations. It provides a non-invasive, large-scale, and continuous method for monitoring biodiversity and environmental changes, which is particularly valuable in conservation and ecological studies.

Applications in Zoology

1. **Habitat Monitoring**
Satellite imagery enables the assessment of habitat extent, fragmentation, and quality. Vegetation indices such as NDVI (Normalized Difference Vegetation Index) help track forest cover, wetland health, and desertification trends that affect wildlife.
2. **Species Distribution and Movement**
By combining satellite data with ground-based observations and GPS-collar tracking, researchers can model species distribution, migration routes, and range shifts in response to climate change or human activity.
3. **Environmental Change Detection**
Satellites detect deforestation, urban expansion, fires, floods, and droughts, providing early warning signals for habitat degradation that may threaten wildlife.

4. **Climate-Responsive Conservation Planning**

Satellite-derived climate data (temperature, precipitation, vegetation cover) are integrated into predictive models to forecast future habitat suitability and vulnerability of species under changing climatic conditions.

5. **Monitoring Human-Wildlife Conflict Zones**

High-resolution imagery helps identify human settlements encroaching on wildlife corridors, enabling targeted mitigation measures.

Internet of Things (IoT) and Edge Devices

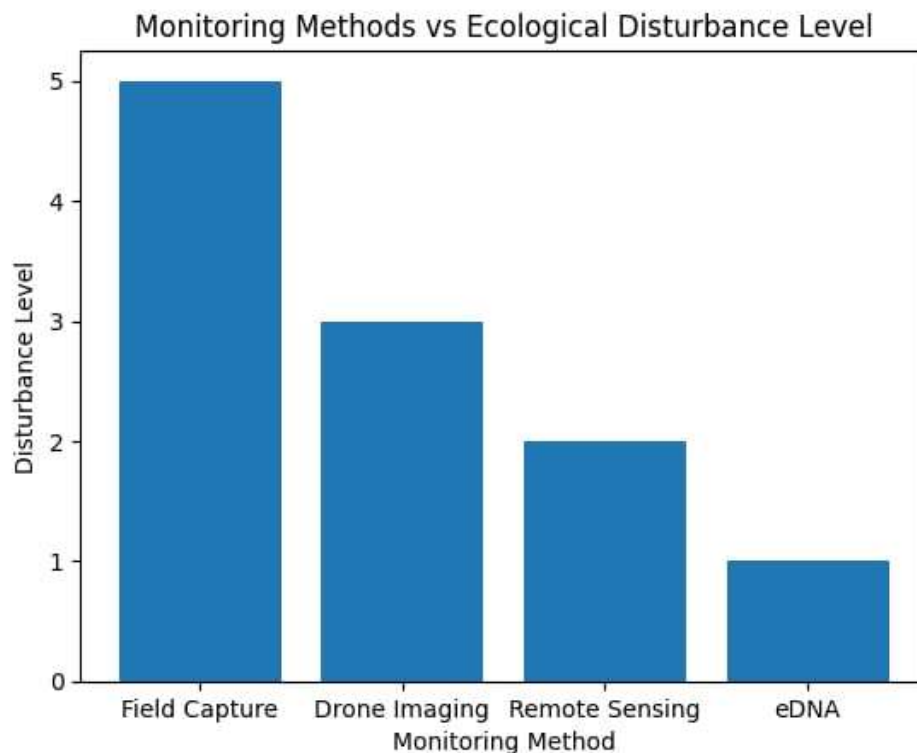
Sensor networks and low-energy computing devices allow real-time collection of environmental parameters such as temperature, humidity, and animal movement, even in isolated regions. These systems support continuous and sustainable data gathering. The Internet of Things (IoT) and edge devices are transforming zoological research by enabling continuous, real-time monitoring of wildlife and their habitats. IoT sensors track environmental parameters such as temperature, humidity, water quality, and soil conditions, while GPS collars, motion sensors, and RFID tags monitor animal movement and behavior. Edge devices allow data to be processed locally, enabling rapid alerts for unusual activity, human-wildlife conflict, or health issues without constant human presence.

IoT systems also support early warning systems for conflict mitigation, monitor wildlife health, and generate large datasets that can be integrated with AI for predictive analysis of habitat suitability, species distribution, and ecological risks. These technologies reduce wildlife disturbance, improve data accuracy, and allow long-term, large-scale conservation studies. Future developments include energy-efficient devices, AI integration for autonomous decision-making, and real-time connectivity with climate models and biobanking databases for holistic wildlife management.

Genomics and Molecular Approaches

Environmental DNA (eDNA)

eDNA analysis enables detection of species through genetic traces present in environmental samples such as water or soil. This non-invasive method is particularly effective for monitoring rare or elusive organisms.



The Role of AI in Genomic Sequencing and Analysis

Artificial Intelligence (AI), including Machine Learning (ML) and Deep Learning (DL), has become integral to modern DNA analysis due to the massive scale, complexity, and heterogeneity of genomic data generated by next-generation sequencing (NGS) technologies. These AI approaches help automate and enhance tasks such as base calling, sequence alignment, variant detection, DNA methylation profiling, and functional annotation. PubMed

Traditional bioinformatics pipelines struggle with large NGS datasets, requiring extensive computation and manual intervention. AI models offer significant improvements in efficiency, scalability, and accuracy, enabling researchers to extract biological insights more comprehensively. (eurekaselect.com)

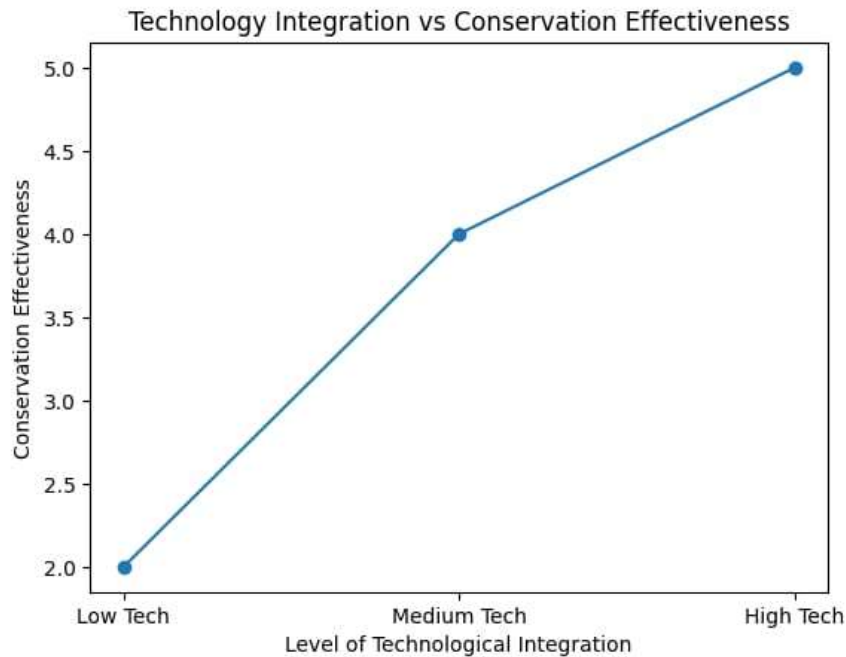
Key AI-Enabled DNA Analysis Tasks

- 1. Base Calling and Read Processing**
In NGS workflows, the first step is translating raw electrical or optical signals into nucleotide sequences (base calling). AI-enhanced tools such as RNNs (Recurrent Neural Networks) and transformer models improve base calling by reducing noise and error rates, especially in long-read platforms. This leads to higher fidelity reads that improve downstream analyses like variant calling. ibri.org.in
- 2. Sequence Alignment and Assembly**
Accurately mapping millions of short reads to reference genomes is computationally intensive. Traditional aligners (e.g., BWA, SNAP) are effective but can be slow or limited in handling repetitive regions. AI-based aligners and machine learning enhancements integrate learned features for improved alignment accuracy and speed. In some comparisons, AI-enhanced tools show higher mapping precision (>92%) and better variant calling sensitivity. bioscipublisher.com
- 3. Variant Calling and Structural Analysis**
One of the most significant contributions of AI in genomics is variant identification — recognizing differences such as SNPs (single nucleotide polymorphisms), indels, and structural variants. Deep learning architectures like CNNs and hybrid models can identify complex patterns not easily captured by traditional heuristic methods, especially in cancer genomics and precision medicine contexts.
. Specialized Applications: Epigenomic and Functional Analysis
- 4. DNA Methylation Profiling**
DNA methylation — chemical modification of DNA — is a key epigenetic marker implicated in gene regulation and disease. Recent studies demonstrate that AI and deep learning models can analyze methylation data more effectively than classical statistical methods. These models can learn intricate methylation patterns across genomes, aiding in the discovery of disease biomarkers and personalized diagnostics.
OUP Academic
- 5. Large Language Models for DNA Sequences**
Emerging AI strategies treat DNA sequences as “biological language,” using Large Language Models (LLMs) to capture complex sequence dependencies. These models can predict regulatory elements, structural motifs, and functional impacts of variants by learning patterns from millions of genomic sequences. This paradigm provides a flexible and generalizable framework for genomic interpretation.
- 6. AI for Clinical and Research Applications**
AI-driven DNA analysis supports numerous high-impact applications:
Cancer Genomics: AI identifies somatic mutations with high sensitivity and helps subtype tumors for personalized treatments.
Precision Medicine: By combining genomic and clinical data, machine learning models can predict disease risk and drug response. dnascientific.com
Nanopore & Single Molecule Sequencing: Experimental AI-based systems can classify individual nucleotides using electrical and molecular fingerprints, showing near-perfect classification accuracy in some cases. RSC Publishing.
- 7. Advantages of AI in DNA Analysis**

Benefit	Explanation
Scalability	Handles terabytes of sequencing data efficiently
Precision	Reduces base calling and variant calling errors
Automation	Minimizes manual intervention and human error
Pattern Detection	Learns complex genomic signatures beyond human intuition
Clinical Relevance	Predicts disease risk and treatment responses

Conservation Genetics

Genomic tools help evaluate genetic diversity, identify inbreeding risks, and assess adaptive capacity, which are critical for species conservation strategies.



Biobanking and Cryopreservation

Storing genetic material in biorepositories safeguards biodiversity resources and supports future breeding or restoration programs. Biobanking and cryopreservation are advanced conservation technologies used to store biological materials of animal species for long-term use. These methods support: Wildlife conservation, Genetic diversity preservation, Assisted reproduction, Species recovery programs. They are especially critical for endangered, rare, and threatened species.

What is Biobanking in Zoology?

A zoological biobank is a facility that stores biological samples under controlled conditions for research and conservation.

Types of Biological Materials Stored	
Material	Purpose
Sperm & Eggs	Assisted breeding programs
Embryos	Species restoration
DNA / Tissue samples	Genetic studies
Blood / Serum	Disease monitoring
Cell lines	Cloning & genetic research

Biobanks act as “genetic libraries” safeguarding biodiversity.

2. Cryopreservation: The Core Technology

Cryopreservation is the process of preserving cells or tissues at ultra-low temperatures, typically: -196°C in liquid nitrogen. At this temperature, biological activity stops, preventing degradation.

3. Cryopreservation Process

Step 1: Sample Collection, Semen collection from mammals, Egg/embryo retrieval, Tissue biopsy

Step 2: Addition of Cryoprotectants Substances like: Glycerol, Dimethyl sulfoxide (DMSO)

Ethylene glycol. These prevent ice crystal formation that damages cells.

Step 3: Controlled Freezing, Gradual cooling ensures cell survival.

Step 4: Storage Samples are stored in liquid nitrogen tanks.

Step 5: Thawing and Use Samples can later be used for: Artificial insemination

IVF (In vitro fertilization)

Genetic studies

4. Applications in Zoology

Conservation of Endangered Species

Cryobanks store genetic material of species at risk of extinction (e.g., rhinos, tigers, amphibians). Assisted

Reproductive Technologies (ART): Stored sperm and embryos help in: Artificial insemination, Embryo transfer.

Role in Sustainable Zoology

Benefit	Impact
Reduces need for repeated wildlife capture	Lower stress on animals
Preserves biodiversity long-term	Ecological sustainability
Supports reintroduction programs	Ecosystem balance

Current Challenges and Limitations

Despite transformative potential, AI-based DNA analysis faces several challenges:

Interpretability: Complex models (especially deep learning) are often “black boxes,” making biological explanations difficult without explainable AI methods.

Training Data Bias: Models trained on limited or biased datasets may not generalize well across diverse populations.

Computational Demand: AI models require substantial computing resources, especially for large genomic datasets.

Big Data, Citizen Science, and Open Platforms

- **Global Biodiversity Databases**

Open-access platforms such as GBIF and animal movement databases facilitate international collaboration and large-scale ecological analysis.

Public Participation in Data Collection

Mobile applications and online platforms allow citizen scientists to contribute species observations, significantly expanding available biodiversity data while promoting public engagement in conservation.

- **Ethical Data Governance**

Ensuring data accuracy, privacy, and fair access remains an important aspect of sustainable scientific collaboration. Ethical data governance in zoological and AI-driven research refers to the responsible collection, management, storage, sharing, and application of biological and ecological data. With the rapid adoption of technologies such as artificial intelligence, genomics, remote sensing, drones, and biobanking, researchers now generate large volumes of sensitive information. Without appropriate governance, these data can be misused in ways that threaten biodiversity, violate ethical standards, or harm conservation efforts.

In modern zoology, researchers routinely collect species location data, genetic information, camera trap images, drone footage, and bioacoustic recordings. Such information, if not properly secured, can pose serious risks. For example, publishing precise geographic coordinates of endangered species may unintentionally assist poachers or illegal wildlife traders. Therefore, ethical data governance plays a crucial role in ensuring that scientific data are used only for legitimate conservation and research purposes.

Several core principles guide ethical data governance in zoological studies. Transparency requires researchers to clearly document how data are collected, processed, and used. Accountability ensures that scientists and institutions take responsibility for ethical data handling. Privacy and protection involve safeguarding sensitive information, particularly species location and genetic data. Data integrity emphasizes maintaining accurate, unbiased, and high-quality datasets. Access control limits who can view or use sensitive data, while benefit sharing ensures that local communities and stakeholders gain from conservation research outcomes.

There are multiple ethical risks associated with zoological data. Location data misuse is a major concern because it can expose vulnerable species to illegal exploitation. AI data bias is another issue, as machine learning models trained on incomplete datasets may underrepresent rare or less-studied species. Genetic resource exploitation can lead to biopiracy if biological samples are used without proper authorization or benefit-sharing agreements. Additionally, unregulated drone monitoring may cause stress or disturbance to wildlife populations. To address these concerns, several governance strategies are implemented. Data anonymization techniques help obscure sensitive species locations. Ethical review boards evaluate research proposals to ensure compliance with ethical standards. Secure databases with restricted access prevent unauthorized data use. Researchers also follow FAIR data principles—making data findable, accessible, interoperable, and reusable—while applying safeguards for sensitive information. Community consent and respect for indigenous knowledge systems further strengthen ethical research practices.

In AI-based zoological research, ethical governance also involves ensuring that algorithms are trained on diverse and representative datasets to minimize bias. Transparency in AI models, often referred to as explainable AI, allows researchers to understand how decisions are made. Regular auditing of AI systems helps detect and correct errors or biases, and controlled data sharing policies reduce the risk of misuse.

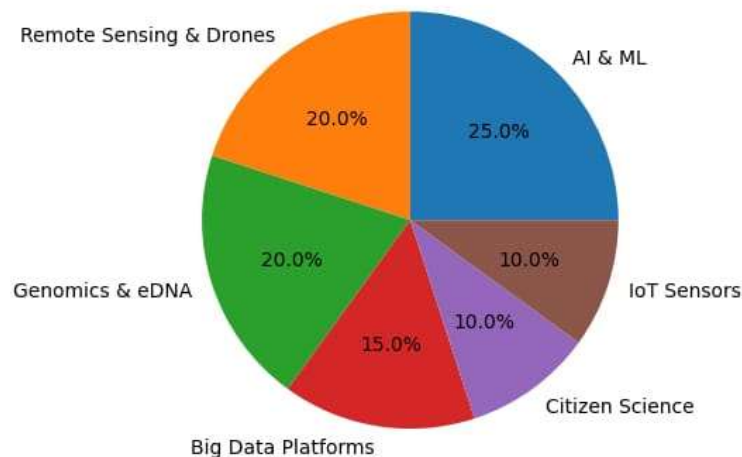
Ethical data governance is supported by international legal and policy frameworks. The Convention on Biological Diversity promotes sustainable use of biological resources, while the Nagoya Protocol regulates access to genetic resources and ensures fair benefit sharing. Institutional Animal Ethics Committees and wildlife data protection policies further guide responsible research practices.

Ultimately, ethical data governance is essential for aligning technological advancement with conservation goals. It ensures that modern zoological research protects biodiversity, respects communities, and maintains scientific integrity. By implementing strong governance systems, researchers can use powerful tools like AI and genomics in ways that support long-term ecological sustainability rather than create new risks.

Immersive Technologies in Zoological Education

Virtual and augmented reality technologies enhance learning by simulating ecosystems and wildlife interactions. These tools improve student understanding and strengthen conservation awareness without disturbing natural habitats.

Contribution of Technologies in Modern Zoology



Sustainability and Ethical Integration

Climate-Responsive Modeling

Combining ecological data with climate projections enables researchers to design adaptive conservation measures that anticipate environmental change. Climate-responsive modelling is the use of computational, statistical, and AI-based tools to predict how climate change affects wildlife, habitats, and biodiversity. It combines climate variables such as temperature, rainfall, and extreme weather with species data to forecast future ecological changes.

In zoology, these models are mainly used to predict species distribution shifts as animals move to more suitable environments due to warming climates. They also assess species vulnerability by evaluating whether organisms can adapt, migrate, or face extinction. Habitat suitability analysis using GIS and remote sensing helps identify areas that may remain stable or become unsuitable under future climate conditions.

Climate-responsive modelling also studies ecological interactions, such as changes in migration timing, breeding cycles, and food availability. Artificial intelligence improves prediction accuracy by analyzing large environmental and biological datasets.

Overall, climate-responsive modelling supports conservation planning by identifying high-risk species, designing climate-resilient protected areas, and guiding adaptive wildlife management strategies.

Mitigating Human–Wildlife Conflict

Technological solutions such as automated alert systems and monitoring sensors help reduce negative encounters between humans and wildlife. Mitigation of human–wildlife conflict increasingly uses Artificial Intelligence (AI) to reduce negative interactions between people and wild animals while protecting livelihoods and biodiversity. These conflicts arise when wildlife damages crops, livestock, or property, or threatens human safety, often due to habitat loss and human expansion.

AI-based systems enhance early warning and monitoring. Camera traps and surveillance systems equipped with AI image recognition can automatically detect animals such as elephants, tigers, or leopards near villages or farms and send real-time alerts. GPS collar data analyzed through machine learning helps predict animal movement patterns and identify high-risk zones. Drones with AI vision are also used to monitor wildlife near human settlements without disturbing animals.

AI supports habitat and land-use planning by analyzing satellite and environmental data to identify wildlife corridors and prevent habitat fragmentation. Predictive models forecast conflict hotspots based on seasonal patterns, climate data, and past incident records.

Community-based mitigation also benefits from AI through mobile apps that allow rapid reporting of wildlife sightings, which feeds into centralized databases for response planning. Non-lethal deterrent systems, such as automated sound or light devices triggered by AI detection, help keep animals away from farms. Overall, AI strengthens traditional mitigation methods by improving monitoring accuracy, enabling early intervention, and supporting data-driven conservation strategies for long-term human–wildlife coexistence.

Responsible Use of Technology

The ecological impact of research tools, ethical data handling, and equitable technology access must be considered to ensure sustainability. Artificial Intelligence (AI) and machine learning are powerful tools in modern zoological research, supporting species identification, ecological monitoring, predictive modeling, and conservation planning. However, their responsible use is critical to ensure that technological advances do not inadvertently harm wildlife, ecosystems, or human communities.

Responsible AI use begins with ethical data collection. Sensitive information, such as species location, breeding sites, or endangered populations, must be secured to prevent misuse, including poaching or habitat exploitation. Data should be anonymized where necessary, and access should be restricted to authorized researchers. Model transparency and validation are also essential. AI algorithms should be interpretable to ensure that predictions, such as species distribution or human–wildlife conflict hotspots, are reliable and unbiased. Regular model audits and cross-validation with field data reduce errors and improve ecological accuracy.

In field applications, AI technologies must be deployed minimally invasively. Drone surveillance, camera traps, and acoustic sensors should be used in ways that minimize stress or disturbance to animals. For example, drones should follow regulated flight paths and altitudes, and sensors should avoid disrupting natural behaviors. Finally, responsible AI use includes community engagement and conservation benefit sharing. Local communities should be informed about AI monitoring activities, trained in reporting wildlife observations, and involved in decision-making processes. The integration of AI should aim to enhance conservation outcomes, support sustainable research practices, and foster coexistence between humans and wildlife.

Overall, responsible AI use ensures that technological innovation in zoology promotes scientific accuracy, ethical standards, ecological sustainability, and societal trust.

Future Directions

Future zoological research will depend on interdisciplinary collaboration that merges biological sciences with data science, engineering, and environmental policy. Sustainable innovation, inclusive data practices, and global cooperation will be central to progress. The future of zoological research lies in the integration of advanced technologies with sustainable conservation practices. Artificial intelligence (AI) and machine learning will play an increasingly central role in automating species identification, predicting human–wildlife conflict, and monitoring ecological changes in real-time. Future AI models are expected to incorporate multi-modal datasets, including images, audio, GPS tracking, and genomic information, to provide more accurate and dynamic insights into wildlife populations and behavior.

Climate-responsive modelling will continue to improve, leveraging high-resolution climate projections and machine learning algorithms to predict species distribution shifts, habitat suitability, and ecosystem responses under different climate scenarios. These models will support proactive conservation planning, including the identification of climate refugia, wildlife corridors, and priority areas for habitat restoration.

Biobanking and cryopreservation will expand, with emerging technologies enabling the storage of stem cells, reproductive cells, and genetic material for a wider range of species. Integration with AI-based data management systems will optimize sample tracking, predictive viability analysis, and accessibility for research and restoration programs.

Responsible and ethical deployment of technology will remain a priority. Future research must focus on transparent, explainable AI models, secure handling of sensitive ecological and genetic data, and community-inclusive conservation strategies. Incorporating citizen science platforms will further enhance large-scale biodiversity monitoring while fostering public engagement in conservation.

Finally, future directions include the development of real-time, automated conservation decision-support systems. By combining AI, remote sensing, climate models, and biobanking databases, researchers will be able to rapidly assess risks, predict population declines, and implement mitigation strategies to protect endangered species and ecosystems. These integrated approaches will advance sustainable zoological research and strengthen global biodiversity conservation.

Conclusion

The integration of emerging technologies such as Artificial Intelligence (AI), climate-responsive modelling, biobanking, and cryopreservation is transforming modern zoological research, providing unprecedented opportunities for biodiversity conservation and sustainable ecosystem management. AI and machine learning enable

accurate, real-time species identification, predictive analysis of human–wildlife conflict, and genomic data interpretation, reducing the reliance on labor-intensive fieldwork and minimizing disturbance to wildlife. Climate-responsive models further enhance conservation planning by forecasting shifts in species distribution, habitat suitability, and ecological interactions under varying climate scenarios, allowing proactive mitigation of climate-driven biodiversity loss.

Biobanking and cryopreservation preserve the genetic diversity of endangered and threatened species, safeguarding them against population declines, habitat loss, and extinction. When coupled with AI-based data management, these tools facilitate the tracking, viability assessment, and strategic deployment of genetic resources in breeding and restoration programs. Moreover, the responsible and ethical application of these technologies—including adherence to data governance principles, algorithm transparency, and community engagement—ensures that technological advances contribute positively to both wildlife protection and human livelihoods.

The convergence of these approaches underscores a broader paradigm shift in zoology: from reactive, observational research to predictive, data-driven, and sustainable conservation science. Future developments are expected to integrate multi-modal AI, advanced climate models, and real-time decision-support systems, enabling rapid assessment and intervention in conservation challenges. By fostering collaboration between scientists, policymakers, and local communities, these technologies not only enhance the effectiveness of conservation strategies but also promote coexistence between humans and wildlife, supporting the long-term resilience of ecosystems.

Ultimately, the adoption of AI and allied technologies represents a transformative step toward harmonizing scientific innovation with ecological stewardship, ensuring that conservation efforts are evidence-based, ethically responsible, and capable of addressing the complex challenges posed by climate change, habitat degradation, and biodiversity loss.

The integration of modern technologies with sustainability principles marks a significant evolution in zoological research. These advancements enhance scientific understanding and conservation effectiveness, yet they must be implemented responsibly to maintain ecological balance and ethical integrity.

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