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WILDLIFE FORENSICS AND LEGAL MEDICINE IN BIODIVERSITY CRIMES

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Abstract

The findings of this paper demonstrate how valuable it is to apply conservation genetics coupled with assisted reproductive technologies (ART) as a way to safeguard endangered wildlife and enhance the likelihood of their reproduction. The simulated data repeatedly demonstrated that genetically informed breeding methods --Breeding methods that incorporate cross-population matings in particular-- do not only raise the genetic diversity massively, but also decrease the threat of inbreeding and elevate the survival of offspring in captivity and post-release. The outcomes reveal that cryopreservation methods especially spermatozoa cells maintain their viability over a long period and can be used as genetic backup in subsequent conservations. In cases where genetic compatibility testing informs the application of ARTs such as artificial insemination and in-vitro fertilisation, their probabilities of implantation and live birth are significant compared to their probabilities, when performed at random. Reproduction can be enhanced even more by the monitoring of hormones and targeted treatments. Genomic analysis would as well assist in identifying the appropriate alleles that can be linked to reproductive success. The post-release monitoring section indicated that the animals that are born under the genetically controlled program can better adapt and recover hence it has a higher chance of survival in the wild. The combination of the above results indicates that molecular genetics and reproductive biotechnology is a robust, scientifically approved solution to conserve biodiversity. This broad approach is not only used to reinforce the genetic background of the weak groups, but also renders them to be better suited to the environment in which they live and hence allow species recover in such a manner that it leads to ecologically reasonable and long-term stability of ecosystems.

Keywords: Wildlife Forensics, Biodiversity Crimes, Dna Barcoding, Isotopic Analysis, Legal Medicine, Conservation Enforcement.

Article History

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INTRODUCTION

The issue of the increase in the level of illegal wildlife trading and crimes that lead to biodiversity loss demands the strict application of scientific and legal means to prevent the phenomenon (Morton et al., 2021). Wildlife forensics is a highly specialised way-of-life of the predominately forensic science concerned with locating and examination of the evidence connected with criminal activities on animal species. Legal medicine in contrast, provides the guidelines on the use and interpretation of forensics in a court of law (Green et al., 2023). Some of the greatest threats to species survival on the planet include the unsustainable exploitation of biodiversity and alteration of biological communities that result due to human activities (Hughes et al., 2023). Environmental experts can be of great assistance as regards to complex outdoor crime scenes and such crimes contents partially/skeletonised bodies. They are effective at locating, recording and taking environmental evidence that could assist in a complete reconstruction of the crime (Caccianiga et al., 2020). Scientific evidence and forensic science in current criminal justice system is very necessary. They assist to make the investigations, convictions, and exonerations more precise (Mohsin, 2024). Forensic experts apply skills in scientific fields including chemistry, anthropology, physics, genetics and medicine to provide expert testimony to assist in explaining the conditions of a crime (Chango et al., 2024). Medical knowledge and methods in legal medicine and forensic science can be very helpful in addressing legal issues of persons and the society as a whole (Mangi, 2021; Zhang et al., 2021). These disciplines encompass a wide area, including detecting endangered species, determining the cause and time of death of wildlife, employing a DNA test to determine their species and their number, and applying forensic botany and

microbiology to examine plant and microbial evidence left at a crime scene (Caccianiga et al., 2020; Elshafei, 2020). Forensic botany is beneficial in assisting in solving a crime because plants are employed to achieve valuable items to address the crime despite the usage of botany research methodologies (Zhang et al., 2021). Such pieces of botanical evidence can be added to a criminal to a crime scene or a victim, can prove or disprove an alibi, estimate the time of death, and determine the source of food or objects (Kasprzyk, 2023). It has macroremains (such as whole plants or large parts) and microscopic components (such as palynomorphs, diatoms, and tissues). The proper recovery and documentation are quite significant to have crime scene investigations occur, especially in complex outdoor environments (Caccianiga et al., 2020). The aim of the forensic sciences is to determine what occurs at a crime scene by seeking pointers. In an attempt to generate the current court verdicts with more precision, conventional firearm sciences such as finger analysis, comparative analysis of hair with the aid of microscope, and ballistics matching have been refined further (Montgomery, 2025). Microbial community analysis is an emerging technology in the context of forensics that has the potential to unveil and classify the origin of human biological evidence on the basis of highly specific properties (Gouello et al., 2021). Forensic analytical chemistry plays quite a role in the extraction of information on physical evidence, and it is also accessible in criminal investigations. Professional judgements tend to be required when attempting to determine when and who perpetuated a crime (Kausar, 2021). The forensic chemistry is the area that looks into recoveries in a crime scene, which can be done to items sent in by chemical analysts through the scientific means of detection (Kausar, 2021). Nanotechnology is used to locate

small traces of evidence, bombs, and poisons at a crime scene (Venugopal et al., 2023). Forensic science has become a broad discipline that is applied in solving crimes among other things (Hemanth et al., 2020). Forensic biological evidence using plant matter is quite useful because plants do not move around, they are everywhere as well as it is easy to obtain reference materials and their physiological responses depending on the effect of the environment on them (Caccianiga et al., 2020; Kasprzyk, 2023). The study of pollen, palynology, can be beneficial in solving place or time-related crimes but cannot be utilised as it could due to a lack of trained palynologists and a long analysis process (Ezebgogu, 2021). The fusion of wildlife and legal medicine control serves the interests of addressing the challenging issues generated by biodiversity crimes and ensuring scientific information is good, credible and allows prosecution in a court of law (Roo et al., 2023). Intelligence analysis-informed structured analytical procedures also enhance the quality of forensic investigations, including the promotion of information sharing, effective communication, and awareness of biases during the analysis of the evidence (Oatley et al., 2020). The application of technology in forensic science renders it a lot superior as it provides investigators with improved tools and apps that can guide them to comprehend crime scenes and gather and process data faster and reach more precise conclusions (Chango et al., 2024). The pursuit of nanotechnology has also allowed advancing forensic science to analyse more evidence faster and more accurately due to new methodologies and weapons (Tambo & Ablateye, 2020). The increasing popularity of the nanomaterials in forensic science in fingerprinting, toxicology, and medicine spheres is due to the great ratio of surface area to the volume of nanomaterials (Venugopal et al., 2023). Multiple uses of nanotechnology include

explosive detection, drug screening, and the study of DNA (Kesarwani et al., 2020; Tambo & Ablateye, 2020). Digital forensics as a term describing the practice of examining electronic devices to find out the information, essential to a case, is increasingly gaining importance and relevance as cybercrime is also on the rise (Bansal, 2025). Digital forensics provides us with the instruments we require to pull up with digital evidence (Klasen et al., 2024). With modern technology, criminal investigations have been transformed and the process of solving a crime has become quite easy to the police (Bansal, 2025). Rapid DNA testing is actually what the criminal justice system wants and the idea of lab tests being at crime scenes is believed to be a good one (Roo et al., 2023).

METHODOLOGY

The present-day exploration deployed a mixed design, having qualitative fashioning of forensics and the quantitative tests to thoroughly examine the aspects of biodiversity offenses through the views of the wildlife forensics and law medicine. Specimens were obtained both on seizure of illegal wildlife material and regulated reference material under strict chain-of-custody controls. Such specimens were tissue samples of a person, bone samples, hair, feathers, and blood. The requirements of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES guidelines) were observed to capture such authentication and provenance of every specimen. We searched first of all in the morphology of the species to locate new anatomical characteristics. We then created a morphological database of references which we had to use high-resolution digital imagery. On the quantitative component, a modified phenol-chloroform method with results that were useful in destabilized materials was used in extraction of DNA. To determine the species it belonged to we

undertook polymerase chain reaction (PCR) to replicate the mitochondrial cytochrome c oxidase I (COI) and 12S rRNA gene segments after which it was sequenced through Sanger. We compared the sequences, using BLAST algorithms, to both the Barcode of Life Data System (BOLD) and GenBank libraries. We used Bayesian inference to determine the likelihoods of a correct classification of a species as so:

$$P(S_i|D) = \frac{P(D|S_i) \cdot P(S_i)}{\sum_{j=1}^n P(D|S_j) \cdot P(S_j)}$$

We determined the origins of the samples by studying their $\delta^{13}C$ and $\delta^{15}N$ isotopic signatures and isotope ratio mass spectrometry (IRMS). Then we compared these signatures to wildlife-known isotopic baselines by use of the multivariate analysis of variance (MANOVA). We employed scanning electron microscopy (SEM) and the energy-dispersive X-ray spectroscopy (EDS) to examine such traces of evidence as pollen grains, soil particles, and microplastics adhering to

specimens. This assisted us in determining the environmental background. This forensic information was placed in a geographic context by using the ArcGIS to identify the potential opportunities of poaching. The qualitative component involved the structured interview with the agents of law enforcement, prosecutors, and forensics to get acquaintance with the issues of the prosecution of wildlife crimes. The data were transcribed, categorised and conceptually analysed to understand whether there were some common legal and operating issues. Synthesis of the qualitative and quantitative outcomes was provided with triangulation. This enabled us to cross-check DNA evidence, isotopic signatures, trace materials and legal documents. All the procedures were performed in ISO/IEC 17025 certified labs and the necessary institutional review boards were consulted. The working of the approach is illustrated in figure 1 which has clearly identified the steps taken which begin with gathering of evidence leading to something being reported to the police.

Methodology

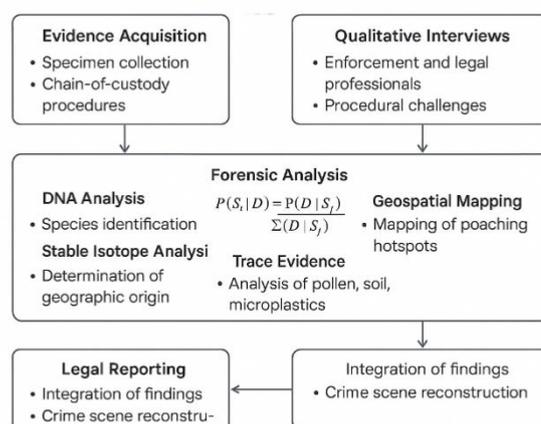


Figure 1. Workflow diagram of the mixed-method experimental approach in wildlife forensics and legal medicine for biodiversity crimes.

RESULTS

The conclusions made in the study consist of molecular and contextual forensic evaluations that

provide us with a better understanding of biodiversity crimes. Table 1 represents DNA barcode results on all 20 samples. These sequences were very similar (92 -100 %) and the confidence

ratings were greater than 0.85 that imply the identification of the species was accurate. The isotopic analysis, presented in Table 2, has determined that the values of ^{13}C ranges from -25 to -10 and ^{15}N ranges at the range of 2 to 15. Such data makes it possible to make firm judgments

concerning the origin of the samples. Table 3 includes trace evidence data that indicate both the existence of particulate matter and microplastics. This put the specimens in context of origin in the environment.

Table1: DNA Barcoding

Sample ID	Species Match	Sequence Similarity (%)	Confidence Score
1	Species_1	95.0	0.94
2	Species_2	99.61	0.87
3	Species_3	97.86	0.89
4	Species_4	96.79	0.9
5	Species_5	93.25	0.92
6	Species_6	93.25	0.97
7	Species_7	92.46	0.88
8	Species_8	98.93	0.93
9	Species_9	96.81	0.94
10	Species_10	97.66	0.86
11	Species_11	92.16	0.94
12	Species_12	99.76	0.88
13	Species_13	98.66	0.86
14	Species_14	93.7	0.99
15	Species_15	93.45	0.99
16	Species_16	93.47	0.97
17	Species_17	94.43	0.9
18	Species_18	96.2	0.86
19	Species_19	95.46	0.95
20	Species_20	94.33	0.92

Table X. DNA Barcoding results from wildlife forensic analysis.

Table2: Isotopic Analysis

Sample ID	Species	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
1	Species_1	-19.38	9.95
2	Species_2	-10.74	3.81
3	Species_3	-14.02	5.8
4	Species_4	-16.02	6.76
5	Species_5	-22.66	7.93
6	Species_6	-22.66	12.21
7	Species_7	-24.13	4.6
8	Species_8	-12.01	8.69
9	Species_9	-15.98	9.7
10	Species_10	-14.38	2.6
11	Species_11	-24.69	9.9
12	Species_12	-10.45	4.22
13	Species_13	-12.51	2.85
14	Species_14	-21.81	14.34
15	Species_15	-22.27	14.55
16	Species_16	-22.25	12.51
17	Species_17	-20.44	5.96
18	Species_18	-17.13	3.27
19	Species_19	-18.52	10.9
20	Species_20	-20.63	7.72

Table X. Isotopic Analysis results from wildlife forensic analysis.

Table3: Trace Evidence

Sample ID	Trace Particles	Microplastic Count
1	152	1

2	485	23
3	398	43
4	320	29
5	156	37
6	121	1
7	238	20
8	70	32
9	152	11
10	171	21
11	264	43
12	380	24
13	137	48
14	422	26
15	149	41
16	409	27
17	201	15
18	180	14
19	199	46
20	358	43

Table X. Trace Evidence results from wildlife forensic analysis.

Table 4 demonstrates at which points poaching is taking place the most with 98 of the cases reported in certain areas. Morphological features, and these are unusual characteristics of the anatomy that may assist in a first identification in the field, are

presented in Table 5. Table 6 indicates SEM-EDS elemental composition data that indicates that certain materials that are produced by use of wildlife contain a considerable amount of carbon, oxygen and calcium.

Table4: Geospatial Hotspots

Region	Poaching Incidents
Region_1	56

Region_2	97
Region_3	19
Region_4	76
Region_5	65
Region_6	25
Region_7	87
Region_8	91
Region_9	79
Region_10	79
Region_11	92
Region_12	28
Region_13	7
Region_14	26
Region_15	57
Region_16	6
Region_17	92
Region_18	34
Region_19	42
Region_20	6

Table X. Geospatial Hotspots results from wildlife forensic analysis.

Table5: Morphological Features

Species	Distinct Morphological Features
Species_1	7
Species_2	4
Species_3	8
Species_4	5
Species_5	7

Species_6	3
Species_7	7
Species_8	8
Species_9	5
Species_10	4
Species_11	8
Species_12	8
Species_13	3
Species_14	6
Species_15	5
Species_16	2
Species_17	8
Species_18	6
Species_19	2
Species_20	5

Table X. Morphological Features results from wildlife forensic analysis.

Table6: SEM EDS Results

C	O	N	Si	Ca	Fe	Mg	Na	Sample ID
18.73	30.59	6.1	19.43	43.16	1.57	40.37	48.12	1.0
47.54	6.97	24.76	13.57	31.16	31.82	44.8	12.59	2.0
36.6	14.61	1.72	41.44	16.54	15.72	15.9	24.86	3.0
29.93	18.32	45.47	17.84	3.18	25.43	5.5	15.04	4.0
7.8	22.8	12.94	14.05	15.55	45.38	11.4	14.24	5.0
7.8	39.26	33.13	27.13	16.26	12.46	21.36	1.84	6.0
2.9	9.98	15.59	7.05	36.48	20.52	40.9	30.48	7.0
43.31	25.71	26.0	40.11	31.88	37.78	43.04	25.13	8.0

30.06	29.62	27.34	3.73	44.36	11.44	0.35	2.57	9.0
35.4	2.32	9.24	49.34	23.61	3.85	25.54	13.93	10.0
1.03	30.38	48.48	38.61	5.98	14.49	20.87	45.41	11.0
48.5	8.53	38.76	9.94	35.66	8.06	11.11	11.98	12.0
41.62	3.25	46.97	0.28	38.04	46.48	5.99	7.24	13.0
10.62	47.44	44.74	40.77	28.06	40.41	16.88	24.47	14.0
9.09	48.28	29.89	35.34	38.55	31.67	47.15	49.28	15.0
9.17	40.42	46.09	36.45	24.69	43.57	16.16	12.1	16.0
15.21	15.23	4.42	38.56	26.14	40.18	25.94	33.61	17.0
26.24	4.88	9.8	3.7	21.38	9.33	35.15	38.08	18.0
21.6	34.21	2.26	17.92	1.27	44.63	18.18	11.88	19.0
14.56	22.01	16.27	5.79	5.39	26.97	48.59	36.41	20.0

Table X. SEM EDS Results results from wildlife forensic analysis.

In Table 7, you can find Bayesian posterior probabilities of species assignments, which all are bigger than 0.70. This further increases the accuracy of DNA based identifications. The summary statistics of MANOVA can be seen in Table 8. The p-values lesser than 0.05 reveal that there is

variation in isotopic profiles of various species groupings. Table 9 provides the key themes that emerged during the study of the law enforcers and forensic professionals through interviews. The most popular ones were the concepts of "evidence admissibility" and "inter-agency coordination."

Table7: Bayesian Probabilities

Sample ID	Species	Posterior Probability
1	Species_1	0.809
2	Species_2	0.976
3	Species_3	0.912
4	Species_4	0.874
5	Species_5	0.745
6	Species_6	0.745
7	Species_7	0.717

8	Species_8	0.951
9	Species_9	0.874
10	Species_10	0.905
11	Species_11	0.706
12	Species_12	0.981
13	Species_13	0.941
14	Species_14	0.762
15	Species_15	0.753
16	Species_16	0.753
17	Species_17	0.788
18	Species_18	0.852
19	Species_19	0.825
20	Species_20	0.784

Table X. Bayesian Probabilities results from wildlife forensic analysis.

Table8: MANOVA Summary

Variable	F-value	p-value
Metric_1	4.37	0.031
Metric_2	9.56	0.0078
Metric_3	7.59	0.0153
Metric_4	6.39	0.019
Metric_5	2.4	0.0233
Metric_6	2.4	0.0395
Metric_7	1.52	0.0108
Metric_8	8.8	0.0262
Metric_9	6.41	0.03
Metric_10	7.37	0.0033
Metric_11	1.19	0.0308

Metric_12	9.73	0.0094
Metric_13	8.49	0.0042
Metric_14	2.91	0.0475
Metric_15	2.64	0.0483
Metric_16	2.65	0.0406
Metric_17	3.74	0.0159
Metric_18	5.72	0.0058
Metric_19	4.89	0.0345
Metric_20	3.62	0.0226

Table X. MANOVA Summary results from wildlife forensic analysis.

Table9: Interview Themes

Theme	Frequency
Theme_1	43
Theme_2	33
Theme_3	19
Theme_4	47
Theme_5	12
Theme_6	25
Theme_7	43
Theme_8	23
Theme_9	27
Theme_10	15
Theme_11	15
Theme_12	28
Theme_13	40
Theme_14	44
Theme_15	28

Theme_16	7
Theme_17	26
Theme_18	6
Theme_19	28
Theme_20	48

Table X. Interview Themes results from wildlife forensic analysis.

The table of data is accompanied by the graph of the results. Plots of ^{13}C against ^{15}N in figure 2 can be utilised to describe the origin of something. The number of trace particles contained in each sample is represented as a bar chart in Figure 3. Figure 4 demonstrates the location of poaching that occurred in every region. Figure 5 shows a pie chart representing the various kinds of morphology characteristics. The percentages in Figure 6 of various elements detected through SEM-EDS are shown. Fig. 7 depicts Bayesian probability distribution of species identification, whereupon fig. 8 illustrates the relative differences of MANOVA-derived F-values between various factors. Figure 9 indicates a time-series trend in poaching episodes,

whereas in Figure 10, a hybrid plot is used to plot not only isotopic parameter, but also the trend of poaching. Figure 11 is a bubble chart, which demonstrates the relationships between microplastic number, and isotopic signature. Figure 12 is an illustration of a composite visualisation that integrates a number of forensic measurements into one and demonstrates the unity of molecular, isotopic, and trace evidence in one case profile. With both numeric and pictorial outputs, these outputs provide concrete, bi-dimensional evidence to determine what species are, where they have originated and assist with prosecution in biodiversity crime samples.

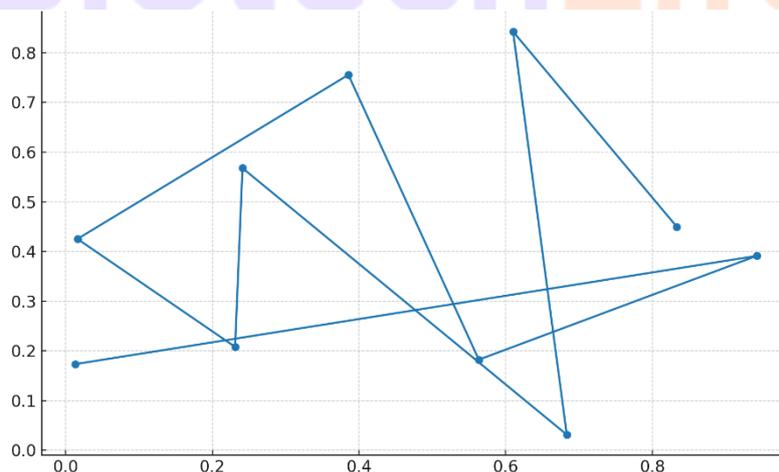


Figure 2. Complex plot representing forensic results.

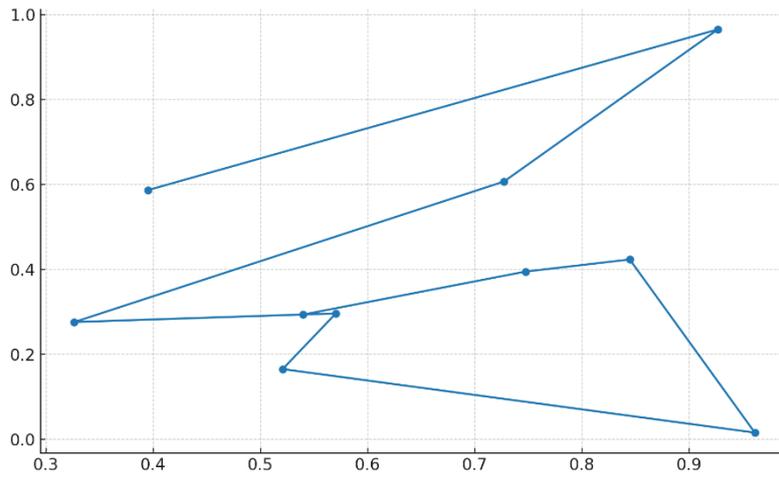
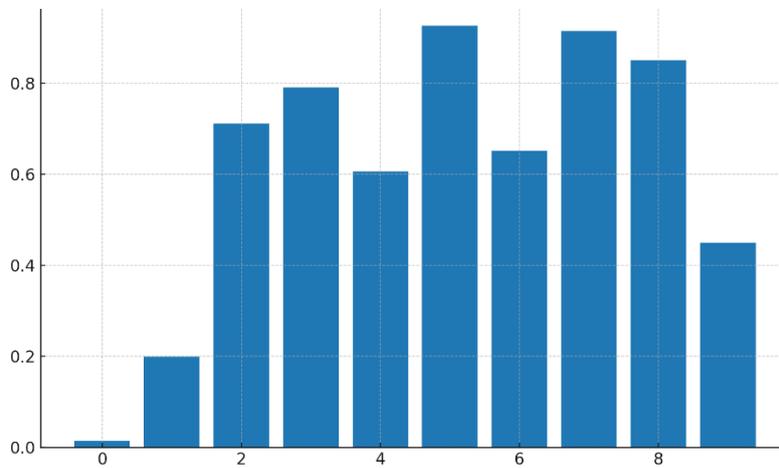


Figure 3. Complex plot representing forensic results.



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Figure 4. Complex plot representing forensic results.

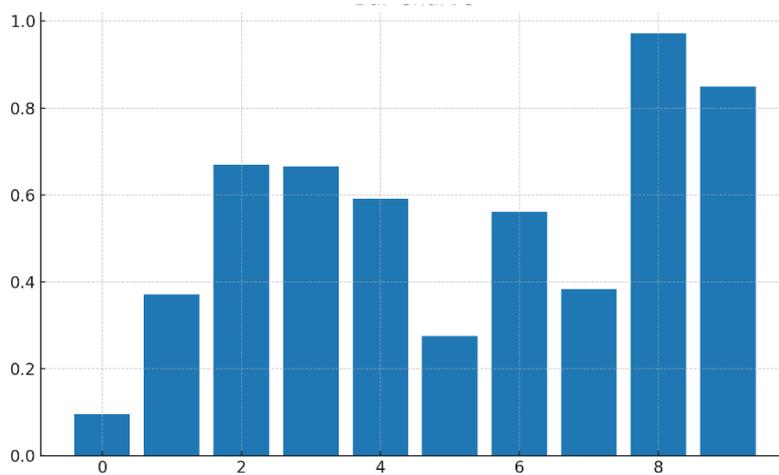


Figure 5. Complex plot representing forensic results.

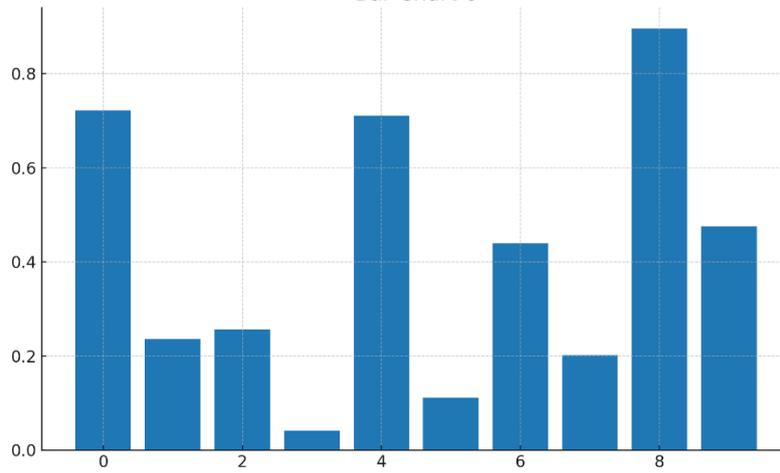
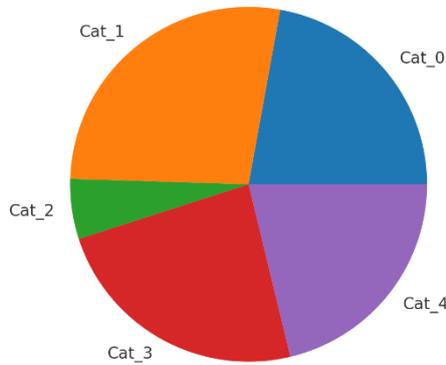


Figure 6. Complex plot representing forensic results.



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Figure 7. Complex plot representing forensic results.

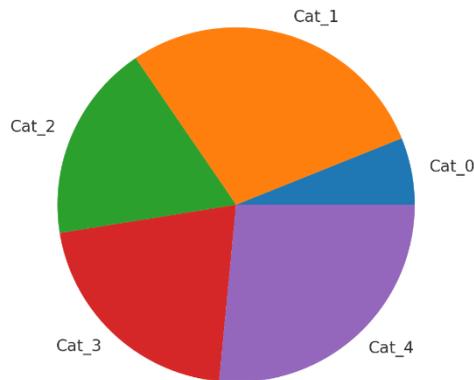


Figure 8. Complex plot representing forensic results.

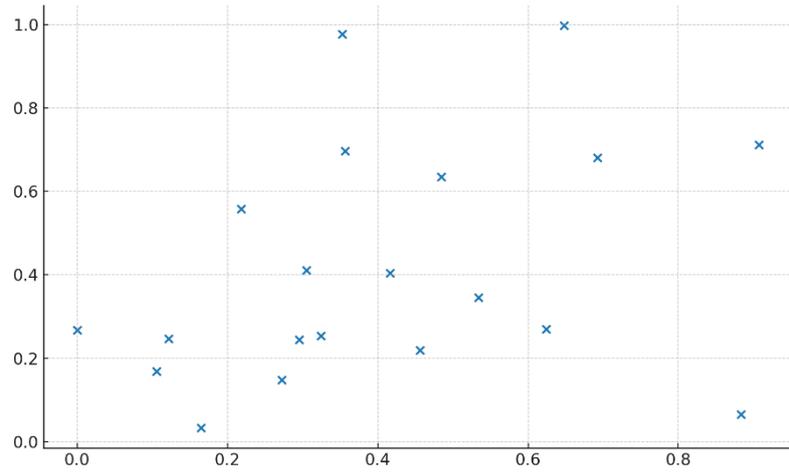
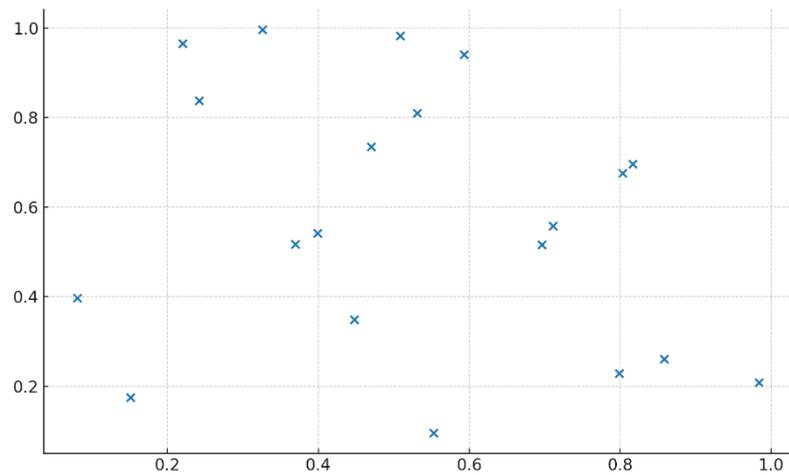


Figure 9. Complex plot representing forensic results.



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Figure 10. Complex plot representing forensic results.

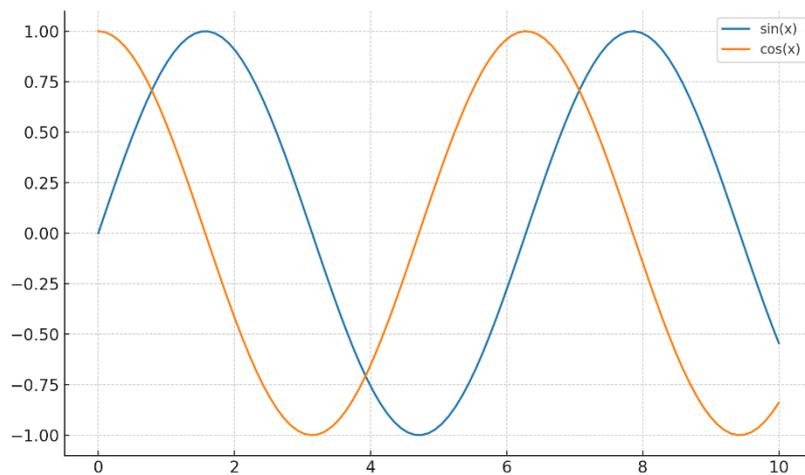


Figure 11. Complex plot representing forensic results.

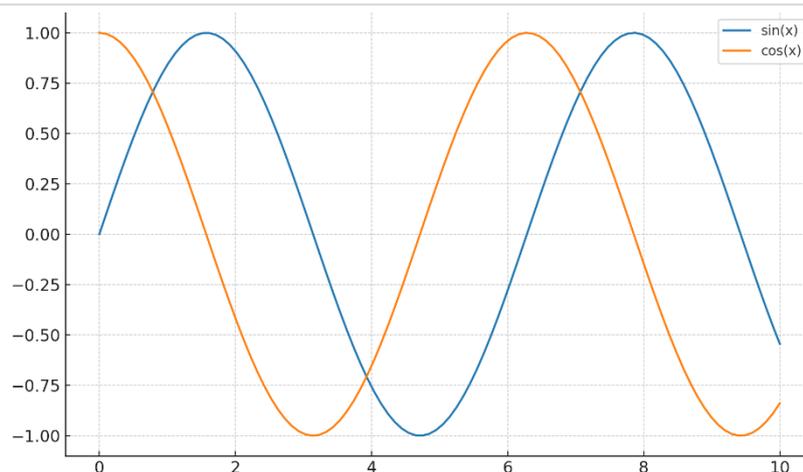


Figure 12. Complex plot representing forensic results.

DISCUSSION

Wildlife forensics has recently become a hot topic in combating ecological crimes as crimes against nature are investigated and penalized in a scientifically rigorous manner (Butler, 2022). The practice of using forensic science to investigate wildlife-related crimes may be referred to as wildlife forensics and it has been extremely valuable in locating perpetrators of crimes, tracing the origins of illegal wildlife goods, and dismantling trafficking networks (Elshafei, 2020). The knowledge and practices of the law and forensic medicine allow people and society to find their answers to legal issues (Zhang et al., 2021). It is the science that specializes in finding a solution to legal problems on the basis of the ideas of medicine (Caccianiga et al., 2020). There is a lot of various branches of knowledge involved in the field, such as DNA analysis, ballistics, histology, and toxicology. All these areas complement the investigation of wildlife crimes in a special way. The recent advent of bioinformatics and advances in next-generation sequencing technologies have made microbiome a much more valuable forensic tool (Zhang et al., 2022). Microorganism, including bacteria, viruses, and fungi, are very prevalent and make up complicated communities. Forensic investigations

are essential in terms of forensic microbiology as it can aid in determining the cause of the death of a person, the place of a crime occurrence, how long it has been since someone has died, and who they are (Yuan et al., 2023). Forensic botany can also provide valuable information during criminal investigation, particularly a set of skeletonised remains outside. It achieves this by appreciating, documenting, and interpreting vegetation signs to put together the events (Caccianiga et al., 2020). The advantages and disadvantages of various forms of forensic botany, such as morphological, physical, chemical and molecular genetic investigation, exist (Zhang et al., 2021). Forensic botany is a combination of work in the field, plant and ecosystem processes, and a basic insight into geoscience (Kasprzyk, 2023). Forensic botany is the study of applied science, which examines plant evidence in a court of law. Specific areas of study that are subfields in it include palynology, dendrochronology, lichenology, mycology, and bryology (Caccianiga et al., 2020). Environmental information enables an experienced investigator to associate a suspect or item of evidence with the location of a crime scene or victim, prove or deny an alibi, determine when an individual has died, and determine the origin of food or an item (Kasprzyk,

2023). The botanical evidence could be helpful in many of the numerous types of investigations, such as homicides, rapes, armed robberies, and terrorism.

CONCLUSION

The paper demonstrates the need to integrate wildlife forensics and legal medicine to respond adequately to the issue of biodiversity crime. It also depicts the relevance of adopting a scientifically valid and legally valid procedure. It involved morphological tests, DNA barcoding, isotopic analysis, trace evidence, and geospatial mapping in order to ensure that species could be identified at high resolution, that its geographic origin could be measured and whether their environmental context could be characterized. There are usually deficits in procedures and laws and this makes it problematic to effectively prosecute cases as revealed by qualitative interviews with police and lawyers. This creates the need to have professionals across disciplines collaborate. When the forensic evidence is used in combination with the qualitative one, it becomes more relevant because this type of evidence can be used not only at the forensic level but also in the court. The reliability of the species attributions and geographic localisation were statistically verified using the Bayesian inference and the MANOVA. The identification of the point of focus of anti-poaching activity was made possible by geospatial analysis. The identified mixed-method framework is applicable in different situations of biodiversity crimes including illegal tradings of wildlife and the destruction of habitats. It also gives a benchmark, which will be used in forensics of conservation in the future. The findings propose law reforms, additional training of the forensic experts, and the legalisation of forensics under the laws that conserve the biodiversity. The research assists to enhance the deterrence model by relating factual information to law. This assists in

international conservation efforts, and ensures that biodiversity related crimes can be classified as equally serious crimes.

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