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Article

Wildlife under threat: Uniting forensic science and conservation practice to safeguard biodiversity

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Abstract: The illegal wildlife trade significantly threatens global biodiversity, driving many species toward extinction and disrupting ecosystems. This transnational crime is fueled by high demand for wildlife products such as ivory, rhino horns, and pangolin scales and is exacerbated by weak enforcement and global trade networks. Conservation efforts aim to mitigate this crisis through habitat protection, anti-poaching initiatives, and public awareness campaigns. In recent years, wildlife forensic science has become an important tool in addressing wildlife crimes. By leveraging techniques such as DNA analysis, radiocarbon dating, and histopathology, forensic science aids in species identification, origin tracing, and criminal prosecution. This paper explores the intersection of illegal wildlife trade, conservation strategies, and forensic science, highlighting their synergistic potential to curb wildlife trafficking. Case studies illustrate how forensic evidence has been instrumental in dismantling smuggling operations and informing conservation policies. The paper also addresses challenges such as resource limitations and the need for international collaboration. Strengthening the integration of conservation efforts and forensic science is imperative to protect endangered species and promote biodiversity conservation.

Keywords: wildlife; crime; threatened species; forensic

1. Introduction

The illegal wildlife trade is a complex global crisis that threatens biodiversity, ecosystems, and the survival of numerous species. "Wildlife trade" refers to the sale and exchange of live wild animals, animal products, or plant resources [1,2]. This illicit market is valued between 7 and 23 billion dollars annually, making it the fourth most lucrative illegal industry worldwide, following drug trafficking, human trafficking, and arms smuggling [3–5]. This illegal activity encompasses poaching, transportation, and the sale of living animals for the exotic pet trade, as well as plants and their derivatives, including animal parts such as ivory, rhino horns, pangolin scales, and meat [1,6].

The illegal wildlife trade has profound consequences for biodiversity, economies, and human health. Overexploitation pushes species like elephants, rhinos, and tigers toward extinction, disrupting ecological balance and reducing genetic diversity.

For example, the African elephant (*Loxodonta africana*) population has declined by over 60% in the past 50 years due to poaching for ivory [7,8]. Between January 2000 and June 2022, an estimated 3377 tigers—both alive and dead, as well as their parts—were confiscated across 50 countries, bringing the species closer to extinction [9]. A Mongabay Indonesia investigation revealed that organized groups killed 26

Javan rhinos (*Rhinoceros sondaicus*)—nearly a third of the species' total population—between 2019 and 2023 [10]. Additionally, shark fishing mortality is projected to reach 80 million sharks per year by 2024, driven by demand for shark fins despite ongoing conservation efforts [11]. Illegal wildlife trafficking imposes substantial economic burdens on countries worldwide, affecting national revenues, conservation budgets, and local economies. In 2013, the estimated economic value of illegal wildlife products entering the USA was approximately $4.3 billion [7]. Namibia invests about $17 million annually in anti-poaching efforts, yielding benefits estimated at $122 million. Without these investments, Namibia could face economic losses of approximately $350 million over ten years [8].

Beyond its ecological impact, the illegal wildlife trade fuels organized crime networks, undermines national security, and exacerbates poverty in source communities. Furthermore, the close interaction between humans and trafficked wildlife increases the risk of zoonotic disease transmission, as seen in the suspected origins of COVID-19 [5,6].

This paper examines the intersection of illegal wildlife trade, conservation strategies, and wildlife forensic science. It highlights the role of forensic methodologies as a tool in combating wildlife crime, securing prosecutions, and advancing conservation efforts.

2. Global trends of illegal trade

An analysis of the World Wildlife Crime Report 2024 indicates that illegal wildlife trade was reported in 162 countries between 2015 and 2021, impacting approximately 4000 plant and animal species [9]. Of these, around 3250 species are listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendices. The trade involves many animal species, including elephants, rhinos, pangolins, tigers, and marine life such as turtles and corals [12]. Notably, approximately 5800 animal species are protected under CITES to prevent over-exploitation through international trade [13,14].

The CITES Illegal Trade Database compiles global data on individual wildlife seizures reported annually by CITES Parties, offering valuable insights into the scale and nature of the illegal trade (**Figure 1**) [13,14]. According to the World Wildlife Crime Report 2024 (WWWCR3) analytical database, the percentage of animal species seized between 2015 and 2021 is as follows: rhinoceroses (29%), pangolins (28%), and elephants (15%), making them among the most trafficked species worldwide (**Figure 1**) [15]. Unfortunately, the absence of standardized global legal trade data makes it difficult and time-consuming to identify trends and draw reliable conclusions. Inconsistent wildlife trade records often result in misinterpretations, posing a major challenge to accurately evaluating the impact of trade on biodiversity and conservation [9].

Almost every country has some illegal animal trading, with the amount and type of trafficked wildlife varying across countries. Some Asian countries and the USA are considered the top destinations, while South America, Asia, and Africa are the top sources of illegal animals [10] (**Figure 1**).

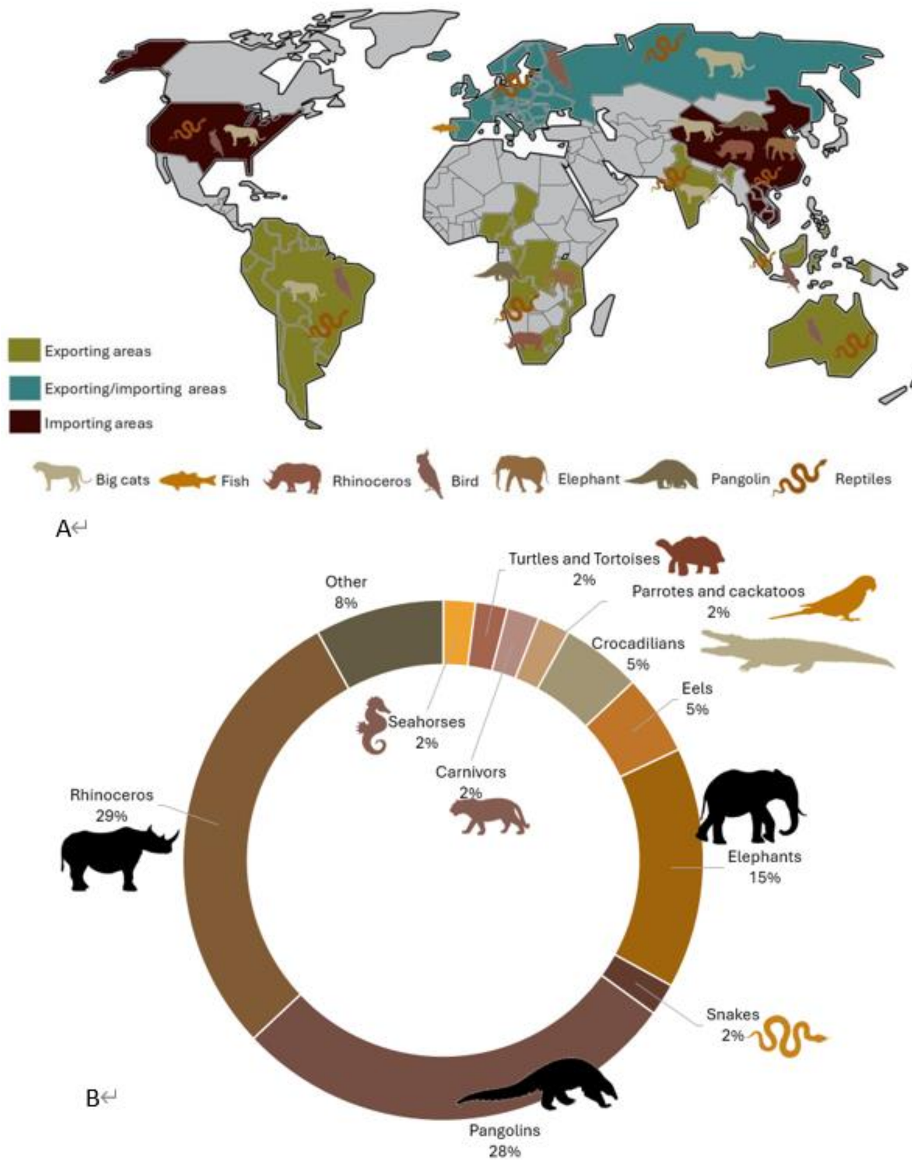

Figure 1. (A) Global map with the main source and destination areas of endangered wildlife species involved in the illegal trade worldwide (source of the data CITES Illegal Trade Database, WWWCR3 analytical database); **(B)** Graphic with the percentage of species group animals' seizure during 2015–2021 globally (adapted from the WWWCR3 analytical database).

Thailand, India, and South Africa are the largest exporters of big cat species. The main importers of these species are China, Thailand, and the USA [10]. Between 2000 and 2022, at least 3377 tigers were confiscated in 2205 seizures across 28 countries. These seizures included 665 live tigers, 654 dead individuals, 1313 whole skins, and 16,214 body parts such as bones, teeth, paws, claws, whiskers, and meat [11]. The Malayan, for example, tiger population has decreased from approximately 3000 in the mid-20th century to around 150 today, primarily due to poaching and habitat loss [12]. Pangolins are considered the world's most trafficked mammals, with estimates suggesting that approximately 100,000 are illegally traded each year. This illicit trade has led to the poaching of over one million pangolins in the past decade, primarily for their scales, which are used in traditional medicine, and their meat is considered a delicacy [11]. The larger exporters are African countries, while the main importers are Asian countries [10]. African countries are also exporters of elephant and rhinoceros products, which are mainly imported to Asian countries [10]. Approximately 35,000 African elephants are killed each year to meet the demand for ivory. This has led to a decrease in wild African populations of individuals [13]. Reptiles, amphibians, and birds in their majority are exported from Asian and South American countries to feed the European, Asian, and American markets as pets or fashion accessories [10]. A study analyzing data from the CITES Trade Database (2000–2019), online trade assessments, and field surveys in Tanzania (2019) revealed key trends: over 1.12 million live chameleons from 108 species were reported as exported between 2000 and 2019. Tanzania alone exported 193,093 chameleons from 32 species, with trade declining over time, mainly for generalist species. Around 41% of Tanzania’s chameleon exports came from one of 23 endemic species, with 10 out of 12 traded endemic species classified as threatened by the IUCN [14]. In the last 10 years, there has been a rise in the trade of helmeted hornbills (*Rhinoplax vigil*) from Sumatra, particularly to feed the Asian markets. Three decades of analysis revealed that 1027 individuals had been auctioned since 1992, with an estimated total auction sales of over US$3 million from 1992 to 2021 [15].

Illegal wildlife trafficking significantly impacts various environments. Terrestrial environments are perhaps the most affected by illegal wildlife trafficking, with high rates of poaching for species like elephants, tigers, and primates [16]. Marine ecosystems also face threats from illegal fishing practices and species trafficking, particularly for sharks and sea turtles. Freshwater ecosystems are less affected but still vulnerable, particularly due to the illegal pet trade and collection of rare species [17].

Within terrestrial environments, forests and savannahs seem to be the ones more affected [18]. Illegal hunting in savannah regions often targets iconic species such as lions, leopards, or elephants [19]. For example, in Senegal’s Niokolo-Koba National Park, big cats are poached for body parts used in traditional amulets [20]. In tropical forest regions like the Lower Guinean forests of West Africa, illegal activities such as poaching for bushmeat and the exotic pet trade pose substantial threats to biodiversity. Species like primates, duikers, and pangolins are particularly vulnerable [21].

3. Why animals are victims of illegal trade

Animals or their parts are used for various purposes, including as food sources, in traditional medicine, in fashion, as ornaments, or as exotic pets [6,15]. Each of these categories has its trends and dynamics, with some operating independently of others (**Figure 2**).

	Source of demand	Nature of commodities	Scale demand	Examples
	Food	Perishable and consumed	Mostly sought in bulk demand, some niche markets	Shark fins, pangolins, eels, sturgeons
	Medicine	Often dried or processed into less perishable form and them consumed	Mostly sought in bulk	Seahorses, big cat bones, pangolins scales, costus root
	Mass market pets and ornamental plants	Live animals and plants dependent of care	Generally sought in bulk	African grey parrot, iguanas, cacti, orchids
	Specialist market for live animals and plants	Live animals and plants dependent of care	Rarity is at premium	Orchids, amphibians, reptiles
	Exclusive market in goods for adornment, display and demonstration of status	Non-perishable and not consumed. Sometimes processed into manufactured goods	Rarity is often a selling point, but sought in bulk	Elephant ivory, rhinoceros horns, rosewoods

Figure 2. Demand clusters, nature of commodities, and scale of demand for species affected by illegal wildlife trade (Source: UNODC).

Animal products play a significant role in the fashion industry, where they are used in items such as fur coats, leather bags, belts, and shoes. Fashion manufacturers are major consumers of wildlife products and, in some cases, unknowingly contribute to the illegal wildlife trade [16,22]. While fur accounts for most of the legal wildlife trade in fashion, reptile skins for leather products are among the most illegally traded items [17]. Although the rise of fur farming has reduced the demand for illegal fur, the demand for reptile skins remains high. Legal reptile farming exists—such as crocodile farms in Kenya and Colombia—but many exported python skins likely come from wild-caught individuals [18]. For instance, large specimens of reticulated python (*Malayopython reticulatus)* skins, often imported into the EU, are unlikely to originate from farms due to the high cost and time required to raise them to slaughter size, making wild capture the more probable source [19,23]. The number of species trafficked for fashion is relatively small [20]. A study of USA confiscations (2003–2013) found that Varanus, Python, Homalopsis, Crocodylus, Caiman, and Alligator accounted for over 80% of fashion-related seizures, with pythons being the most frequently seized [18].

The exotic pet trade is another major component of the illegal wildlife trade. For example, 68% of parrot populations in the Neotropics are threatened due to local pet trade captures, which pose their greatest risk [24]. Many of these species are also sold internationally, with some parrots fetching prices over 1500 times higher in European markets compared to Latin America [25]. Exotic pets primarily include birds and reptiles, although some mammals and invertebrates, such as tarantulas, are also trafficked (**Figure 3**). People acquire exotic pets for various reasons, including personal interest, status symbols, financial investments, and participation in competitions such as bird song contests [26]. High-profile cases include cheetahs as status symbols in Gulf countries and tigers in private collections.

Social media has facilitated wildlife trafficking by publicizing new species and providing platforms for buying and selling illegally traded animals [27]. A study in Mexico found that Facebook hosted the most wildlife-related content, with many people engaging in illegal sales under the assumption that authorities would not investigate [28,29]. E-commerce and social media platforms provide anonymity to traffickers, who use paid advertising and visual content for marketing [30]. While media exposure, such as movies featuring wild species (e.g., snowy owls in Harry Potter, Ninja Turtles, Finding Nemo), was once thought to drive demand for exotic pets, studies have found little evidence to support this claim. However, experts advocate for responsible media representation to promote conservation and discourage wildlife exploitation [31,32].

Wildlife laundering—where illegally sourced animals are falsely labelled as captive-bred—is a major issue in the pet trade. Genetic tools have been developed to detect such fraud, such as identifying wild-caught cheetahs misrepresented as captive-bred in South Africa [25]. Although CITES strictly regulates the trade of species like cheetahs (listed in Appendix I), exceptions allow captive breeding with wild stock augmentation under specific conditions to prevent inbreeding (**Figure 3**). In Brazil, illegal breeding is widespread, with 68% of commercial breeders involved in such activities [33]. Some species previously used in biomedical research, such as Barbary macaques, have gained value in the pet market following a decline in research demand [34].

Nature tourism is often promoted as a sustainable alternative to species exploitation. However, when focused solely on profit, it can negatively impact wildlife [22]. Common practices include restraining, drugging, or mutilating animals to make them more docile for tourist interactions, especially in species like tigers and elephants [34].

Figure 3. Some examples of the species more observed in the exotic pet trade, from left to right, are the Amazonas parrot (*Amazonas* spp.), the Burmese python (*Python bivittatus*), and the Hermann’s Tortoise (*Testudo hermanni*) (photo author: Andreia Garcês).

Traditional medicine utilizes more than 50,000 plant species, 700 fungi, and over 500 animal species globally [35,36]. While legal in many cases, traditional medicine poses significant threats to biodiversity. For instance, 53% of reptile species and approximately 15,000 plant species used in medicinal practices are threatened [36]. However, the true impact remains unclear due to insufficient assessments, complicating conservation efforts that rely on species conservation status. Many animal-based remedies, such as bear bile, pangolin scales, and big cat derivatives, lack scientific evidence of their purported medicinal properties. In some cases, products allegedly containing tiger parts show no detectable traces of tiger DNA [37]. In China, 43% of surveyed individuals reported consuming products supposedly containing tiger parts [38], although 88% were aware of the illegality [39]. While an estimated 13% of traditional Chinese medicines are derived from animals, motivations for their use are shifting. Many products once valued for their medicinal properties are now consumed as luxury items or status symbols rather than for health benefits [40]. For example, approximately 80% of the world's white rhinos (Ceratotherium simum) live in South Africa, where poaching increased dramatically between 2007 and 2014 to meet the demand for rhino horn in the Asian medicinal market [41].

The harvesting and consumption of wild foods are typically legal. However, they become wildlife crimes when protected species are taken or regulations are violated (e.g., lack of permits, off-season hunting) [42]. Unregulated harvesting can have severe consequences for biodiversity. Bushmeat serves as a critical protein source for many low-income and rural households, sometimes representing the only accessible source of protein [43]. However, for wealthier individuals, bushmeat is often consumed as a status symbol. High-income consumers are more likely to eat wild foods as delicacies or luxury items, including pangolin, king cobra, and caviar [6]. Such foods are also consumed in business settings to signal wealth and prestige.

Increasingly, bushmeat is being used as a source of income for low-income households rather than being consumed directly. Organized crime groups have capitalized on this trend, particularly in urban and affluent areas, by acting as intermediaries in the supply chain [23]. This pattern also applies to seafood, particularly caviar, where up to 90% is believed to originate from illegal sources. Practices such as "whitewashing" (falsely labeling wild caviar as farmed or legal) are well-documented [44].

For example, in Ecuador's Yasuní Biosphere Reserve, the illegal bushmeat trade has been increasing. The species most commonly sold include paca (Cuniculus paca), collared peccary (*Pecari tajacu*), white-lipped peccary (*Tayassu pecari*), and woolly monkeys (*Lagothrix poeppigii*). The demand is driven by shift workers visiting the region, rural-to-urban migrants, and domestic tourists seeking traditional food prepared by the Waorani Indigenous people [45].

4. The illegal wildlife trade and its implications for conservation and health

The IUCN Red List identifies at least 5209 animal species as near threatened or threatened due to "use and trade" activities. Overexploitation can result in reduced genetic diversity, population declines, and, in severe cases, local or total extinction of species [23]. Loss of genetic diversity often leads to inbreeding depression, which can further destabilize populations and potentially lead to their collapse or extinction [24]. This risk is particularly acute for species confined to small areas, those with limited population sizes, or when specific traits—such as unique feathers, scales, skin, or fur colors—are targeted for trade, removing those traits from the population [25]. A recent analysis suggests that 18% of vertebrate species face extinction risks from trade-related activities [26]. Poaching of wild animal species frequently involves traps and snares, which can cause significant harm to animal communities [27]. These methods, used legally or illegally, are often indiscriminate, targeting non-specific species and causing extensive animal suffering [28]. For instance, when only specific animal parts or derivatives are sought, ruthless techniques like steel-jaw traps or bear farming for bile extraction are employed [29], often resulting in prolonged suffering or death. When live animals are poached for trade, the mortality rates during trapping, transport, and captivity are alarmingly high [30]. For example, African grey parrots (*Psittacus* *erithacus*) experience mortality rates of 60%–90% before reaching their final destinations [31]. To offset these losses, poachers capture large numbers, further escalating pressure on vulnerable species. Even animals that survive the journey often face high mortality rates in captivity. For example, 75% of exotic reptiles die within their first year as pets.

Poaching also drives behavioral and physical adaptations in some species. Endangered mountain gorillas (*Gorilla beringei beringei*) have learned to recognize and dismantle traps [32]. Similarly, heavily hunted populations of Japanese mamushi vipers (*Gloydius blomhoffii*) show changes such as smaller size, fewer vertebrae, and heightened aggression as a survival response. In some cases, poaching alters the species' phenotypic traits [33]. For instance, the poaching of elephants for ivory has increased the proportion of tuskless female elephants (*Loxodonta africana*) in Africa, as tuskless individuals have a survival rate five times higher than their tusked counterparts [34]. These examples underscore the profound and multifaceted impacts of poaching on wildlife populations. One of the measures to protect white rhinos (*Ceratotherium simum*) is to dehorn the animals to protect them from illegal poaching, which can lead to alterations in their normal behavior, particularly in males [5,35].

Overexploitation of wild biological resources significantly impacts ecosystem health, diversity, and stability. For example, logging is a major driver of biodiversity loss in tropical regions, while poaching disrupts ecosystems by altering species dynamics [36]. Hunting medium and large mammals in the tropics leads to an increase in small mammal populations due to reduced competition and predation, affecting seed dispersal and habitat structure [37]. Removing predators or herbivores alters food web dynamics, potentially leading to overpopulation or extinction of other species. Poaching of keystone species like elephants and large carnivores disrupts ecosystem dynamics [5]. Elephants, for instance, shape habitats for many different species, and their loss can lead to cascading effects [28]. The decline of sea otters from poaching has caused sea urchin overpopulation, destroying kelp beds that protect coastal ecosystems [38]. Local communities dependent on tourism suffer when iconic species disappear.

Illegal trade increases the risk of introducing invasive species, which generate significant economic and ecological costs, estimated at around $160 billion annually [37]. Between 1% and 16% of all species worldwide have invasive potential, often through escape or intentional release, such as unwanted pets. Invasive species compete with native fauna for resources, sometimes suppressing or replacing them. For instance, the Burmese Python (*Python bivittatus*), likely introduced to the U.S.A. via the pet trade or accidental release, has caused significant declines in native species in the Everglades [37]. Similarly, 17.9% of illegally traded reptiles in Australia are predicted to be established as invasive species if they escape [39,40].

Animals or products originating from illegal wildlife trade lack inspections, veterinary screenings, and hygiene standards, facilitating the rapid spread of diseases and pathogens through live animals or wildlife products [41]. Unsanitary conditions in markets heighten the likelihood of disease transmission [42]. Notable examples include African swine fever, introduced to the EU via illegally traded meat, and HIV, transmitted to humans through hunting and butchering non-human primates, causing a global pandemic with over 35 million deaths [43]. Wildlife trade, including bushmeat and exotic pets, poses significant risks for zoonotic disease outbreaks, potentially leading to epidemics or pandemics, as seen with COVID-19 (SARS-CoV-2), likely linked to wildlife trade. Zoonotic diseases, which transfer from animals to humans, account for over 60% of emerging infectious diseases, with 71.8% originating from wildlife [44].

5. The importance of wildlife forensic sciences in the illegal wildlife trade

Forensic science plays an important role in helping address wildlife crime by providing scientific methods to analyze and interpret evidence related to illegal wildlife trade [45,46]. In criminal prosecution, forensic evidence can be used in courts to secure convictions against poachers, traffickers, and illegal traders. Strict legal protocols are followed during evidence collection to ensure admissibility in court [47]. Forensic analyses also support conservation efforts by determining population impacts through the analysis of seized materials, estimating the number of animals killed, and providing data critical for shaping anti-poaching policies and strategies [48]. Moreover, wildlife forensics helps monitor trade networks by identifying common smuggling routes and hotspots, while forensic databases enable the comparison of DNA samples to trace back to poached populations [49,50]. Unfortunately, forensic sciences face several challenges. Many countries lack the infrastructure or trained personnel to conduct advanced forensic analyses [51,52]. Inconsistent legal frameworks across countries further hinder the prosecution of wildlife crimes. Additionally, the clandestine nature of the illegal wildlife trade and complex supply chains make it difficult to trace the origins of products [53,54]. Next is a summary of forensic techniques that are available at the moment for the investigation of wildlife crime:

5.1. Identification of species and physical exam

One key aspect is species identification, which can be from a whole animal dead or alive or only confiscated parts such as ivory, horn, skin, or scales (**Figure 4**) [55].

Figure 4. Some examples of the species that can be observed in illegal trade are: **(A, D)** Hermann’s Tortoise (*Testudo hermanni*); **(B)** Leopard Gecko (*Eublepharis macularius*); **(C)** blue-fronted amazon (*Amazona aestiva*); **(E)** Western Pacific monitor lizard (*Varanus indicus*); **(G)** Moluccan Eclectus (*Eclectus roratus*) (photo author: Andreia Garcês).

Forensic pathologists can contribute through trauma analysis by examining animal remains for signs of trauma, such as gunshot wounds, poisoning, or traps. Also determine the physical condition of the specimen, age/sex, and any presence of rings/microchips/collars or tattoos. [45,51,53]. These examinations not only reveal the cause and method of death but also link specific killing methods to known poaching syndicates, aiding in targeted law enforcement actions (**Figure 5**) [51,56]. Radiology and imaging, such as *X*-rays and CT scans, reveal internal injuries or embedded projectiles [57]. Furthermore, wildlife products are analyzed for pathogens as part of disease and zoonotic surveillance [44]. Samples of blood, tissue, fur, scales, and feces can be collected and sent for further analysis [47]. For instance, ivory from elephants can be distinguished from walrus or mammoth ivory through structural differences [58]. Rhino horn can be identified through keratin structure analysis and isotope tracing [59].

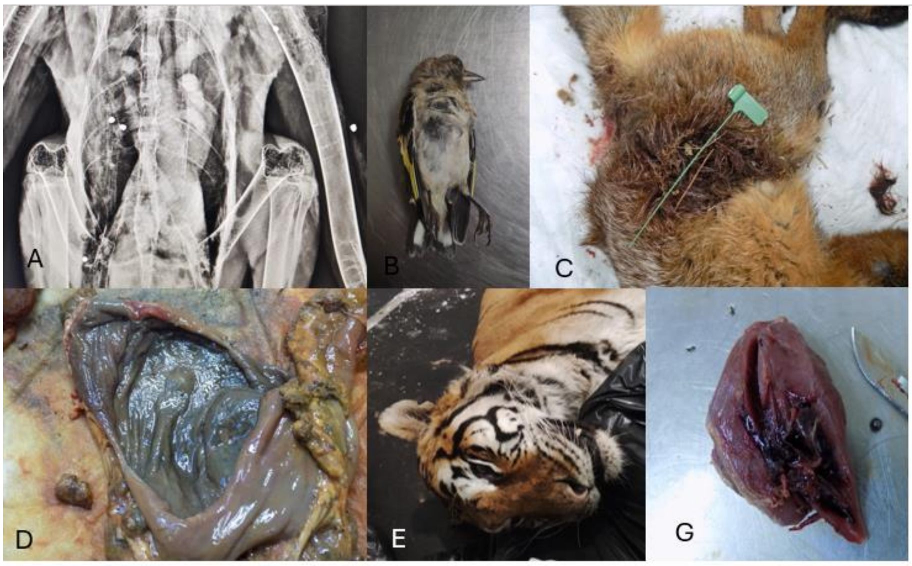

Figure 5. Some examples of lesions possible to observe in animals captured in illegal trade: **(A)** the presence of gunshot pellets in an *x*-ray from a bird; **(B)** passeriform that was captured as an exotic pet but died from malnutrition; **(C)** red fox capture in a trap; **(D)** poison in the stomach contents of a red fox; **(E)** corpse from a Siberian tiger; **(G)** gunshot pellet recovery from the pectoral muscle of a bird (photo author: Andreia Garcês).

5.2. DNA samples

DNA analysis, including mitochondrial and nuclear DNA testing, offers a powerful alternative for species identification when evidence cannot be confidently identified through physical inspection [60]. Techniques like DNA testing and morphological analysis are essential in distinguishing between legal and illegal wildlife trade. It can help to identify species, determine gender, verify family relationships, and conduct individual profiling, especially when physical evidence is inconclusive. DNA analysis offers a powerful alternative for species identification. Specific DNA regions, which vary among species but remain conserved within species, are targeted and sequenced [61]. These sequences are then compared to a validated reference database of known species to determine the specimen's species of origin based on sequence similarity. For animals like deer or wild goats, where hunting regulations vary between males and females, gender identification is crucial. In cases where morphological traits (e.g., antlers or genitalia) are missing due to carcass preparation, DNA analysis can reliably determine gender [62]. DNA analysis of seized ivory has been used to pinpoint the origin of poached elephants in Africa [63].

DNA profiling can also verify family relationships by analyzing genetic inheritance [64]. Each individual's DNA profile must include genetic variants from its biological parents. If discrepancies are found, the individual cannot be their offspring. This method is particularly useful. DNA testing identifies protected shark species in dried fins, which are often mislabeled in international trade [65]. In wildlife conservation, to challenge false captive breeding claims, such as with birds of prey, specific tests are available [13]. The most powerful application of DNA analysis is individual DNA profiling, which links evidence to specific incidents. For example, in cases of illegal hunting, such as coursing, saliva traces from a dog on a hare can be matched to a suspect's dog, providing strong evidence of involvement [52]. Molecular techniques such as mitochondrial molecular markers have been developed for the identification of parrots targeted by illegal trade as the Blue-fronted Parrot (*Amazona aestiva*) [66]. DNA barcoding has helped confirm pangolin species in large-scale seizures [67].

As an example, a paternity test was conducted to solve a robbery case involving Greek tortoises (*Testudo graeca*). Six tortoises were allegedly stolen from a private breeder and later found for sale online by the suspected thief. The stolen tortoises were confiscated by the State Forestry Corps (CFS). To confirm their rightful owner, forensic experts analyzed 14 autosomal microsatellite markers, comparing the genetic profiles of the seized tortoises with ten legally owned individuals from the breeder. This genetic testing helped establish whether the confiscated tortoises indeed belonged to the breeder [68]. In 2007 a man attempted to smuggle valuable bird eggs out of Australia using a specially designed vest. When customs officers informed him of a search, he deliberately crushed most of the 38 eggs, leaving only two intact. DNA analysis was conducted on both the broken and remaining eggs to identify the bird species, as quarantine laws prevented hatching. The Australian Museum's DNA laboratory confirmed that all the species were legally protected. As a result, the man was convicted of wildlife trafficking [69]. In 2017 Vietnam recorded an unprecedented number of rhino horn seizures, and it was necessary to track illegal trade routes. Authorities analyzed the seized horns using DNA profiling. In total, 41 horn samples were tested in Vietnam and then sent to South Africa for comparison with the RhODIS (Rhino DNA Index System) database. This forensic investigation aimed to determine the origins of the horns and help combat wildlife trafficking [70]. In a 2010 poaching case in Cyprus, authorities investigated the illegal killing of the protected Cypriot mouflon (*Ovis orientalis ophion*). A vehicle failed to stop at a checkpoint and was later intercepted, revealing 12 bloodstained items. Nearby, game wardens discovered three freshly killed mouflons, confirmed by veterinary services to have been shot. DNA analysis using the mitochondrial Cytochrome-b gene and microsatellite markers established a genetic match between the bloodstains and the dead mouflons, linking the suspects to the poaching incident [71]. To combat the illegal trade of Bengal tigers (*Panthera tigris tigris*) in Nepal, it was created a genetic database using eight STR markers to profile wild tigers from different geographic regions. Their analysis identified Bardia National Park as a major poaching hotspot [72].

5.3. Aging samples—Stable isotope analysis and radiocarbon dating

Another crucial area is age and origin determination. Methods like isotope analysis allow scientists to ascertain the geographic origin of an animal or product. For instance, age determination techniques such as radiocarbon dating help to estimate the age of ivory tusks, helping to assess whether the product predates bans like the 1989 international ivory trade ban [49]. By analyzing stable isotopes in elephant ivory, it is possible to identify the region where the elephant lived, since they have different isotope signatures based on diet and water sources [73]. Trace evidence from smuggled tortoiseshell products has been matched to Southeast Asian populations, aiding targeted conservation efforts. In another case, to verify whether a rhino horn was legally collected before 1947, when trade restrictions were not in place, scientists used radiocarbon dating. Older samples, such as those from before 1947, contain lower levels of carbon-14 compared to more recent specimens [74].

Stable isotope analysis (SIA) is increasingly used to combat illegal wildlife trade by distinguishing wild from captive animals based on dietary differences. This technique analyzes carbon (13C:12C) and nitrogen (15N:14N) isotope ratios, which vary between natural and controlled diets. SIA has been applied to detect escaped farmed mink and salmon, identify laundered wild reptiles and amphibians in commercial breeding, and differentiate captive from wild echidnas and African grey parrots [75].

5.4. Toxicology analysis

Wildlife poisoning often involves misuse or deliberate abuse of pesticides. Illegal baiting practices, aimed at species like birds of prey, foxes, corvids, and badgers, are widespread around the world [47]. These methods are indiscriminate, often harming non-target species. A small number of highly toxic pesticides, sometimes decanted into unmarked containers or injected into bait with syringes, are commonly used [76,77]. Toxicological analysis plays a crucial role in combating illegal trade since it provides scientific evidence for prosecutions. helps trace the source of illegal wildlife products, aids in policy-making (e.g., banning toxic chemicals used in poaching), and supports early detection of poisoning incidents in protected areas [78]. Techniques of analytical chemistry are employed to detect pesticide residues in animal tissues such as gut contents, vomit, feces, blood, urine, and organs like the liver, kidneys, and lungs. Residues are also analyzed from poisoned bait and environmental evidence. These analyses identify chemical groups, such as organochlorines, organophosphates, carbamates, pyrethroids, anticoagulants, and rodenticides, or individual compounds like strychnine, paraquat, cyanide, and phosphine. Pesticide analysis helps confirm poisoning as the cause of death and can also link suspects to crimes by detecting residues on tools, vehicles, or other relevant items [51,76]. For example, poachers poison animal carcasses to kill vultures, which might alert rangers to illegal kills. In Botswana, over 500 vultures were found dead around elephant carcasses. Toxicological analysis confirmed they were poisoned using carbofuran, a banned pesticide. This evidence helped authorities track poachers who poisoned the birds to avoid detection [79]. In the Czech Republic, illegal fishers use carbofuran-laced bait to kill otters that interfere with their fishing activities [80]. In Maasai Mara, lions were dying mysteriously. Forensic toxicology detected aldicarb (a potent pesticide) in the meat they consumed, confirming deliberate poisoning by herders [81]. Toxicological tests on confiscated reef fish revealed traces of cyanide, proving that fishermen used it to stun and capture live fish for the pet trade. This helped enforce bans on cyanide fishing [82].

5.5. Soil and other compounds analysis

Trace evidence analysis is another significant component of wildlife forensic sciences. Fibers, soil, or pollen collected from confiscated wildlife products can help reconstruct transport routes and locate poaching sites. Additionally, hair, feathers, or other body parts left at crime scenes can be matched to individual animals, providing critical evidence for investigations [52,53]. A hunter in Africa was convicted of poaching after the soil on his clothing matched the protected area where a rhino had been killed [83]. In another case, forensic soil evidence traced smuggled reptiles to Madagascar, proving their illegal export [22].

6. Additional remarks

The illegal wildlife trade remains a significant global challenge, posing severe threats to biodiversity, ecosystems, and human societies [84]. This illicit activity endangers countless species, undermines conservation efforts, and fosters corruption, organized crime, and public health risks. Addressing this issue requires a comprehensive approach that includes strengthening legal frameworks, leveraging technological advancements, fostering global collaboration, involving local communities, and raising public awareness [85].

Strengthening legal frameworks and enforcement is essential to effectively combat wildlife crime [1]. Governments must enhance their legal systems by harmonizing international laws, closing loopholes exploited by traffickers, and imposing stricter penalties for offenders [86]. Enhanced partnerships between countries, non-governmental organizations, and intergovernmental bodies such as INTERPOL and CITES are crucial [16]. Additionally, increasing funding and providing specialized training for wildlife crime units [35], customs officials, and border patrols can significantly improve enforcement efforts [87,88].

The use of advanced forensic techniques can help trace seized wildlife products, identify species, and link crimes to perpetrators [89]. Technological advancements play a crucial role in wildlife protection and enforcement. Emerging tools such as artificial intelligence and machine learning enhance the tracking, monitoring, and reporting of illegal wildlife trade [90]. Blockchain technology ensures transparency in legal wildlife trade and supply chains, reducing opportunities for laundering illegal products [23]. Surveillance tools, including drones and satellite imaging, offer improved detection of poaching activities, particularly in remote and difficult-to-monitor regions [91].

Community involvement is vital in conservation efforts, particularly in poaching hotspots where local populations often face economic hardship [92]. Providing alternative livelihoods can reduce dependence on illegal activities, while integrating indigenous knowledge into conservation programs strengthens traditional environmental stewardship. Promoting sustainable economic activities such as ecotourism, habitat restoration, and conservation-friendly agriculture can contribute to biodiversity preservation while benefiting local economies [3,93]. Public awareness and demand reduction are also crucial in addressing illegal wildlife trade. Education campaigns should highlight the ecological, ethical, and health risks associated with wildlife trafficking [92]. Utilizing digital platforms and social media can amplify conservation messages and mobilise public support [44]. Reducing consumer demand for wildlife products is essential to curbing illegal trade and protecting vulnerable species [33].

7. Conclusions

The fight against illegal wildlife trade is a complex and ongoing challenge. However, with concerted global efforts, innovative solutions, and inclusive strategies, it is possible to reduce and eventually eliminate this threat. Protecting wildlife is not only a moral imperative but also essential for maintaining ecological balance and ensuring the health and well-being of future generations. In the future, global collaboration is essential to enhance data sharing, uniting governments, NGOs, scientists, and local communities in the fight against this global challenge. Technological advances, such as AI and machine learning, can improve the analysis of forensic data and the prediction of trade patterns. Capacity building through training local authorities and wildlife veterinarians in forensic techniques is also critical to effectively addressing wildlife crimes. Wildlife forensic science can be a powerful tool to help combat illegal wildlife trade and protect global biodiversity.

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