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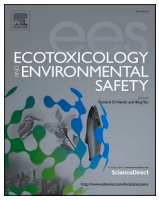

Review

Intersecting planetary health: Exploring the impacts of environmental stressors on wildlife and human health

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ABSTRACT

This comprehensive review articulates critical insights into the nexus of environmental stressors and their health impacts across diverse species, underscoring significant findings that reveal profound effects on both wildlife and human health systems. Central to our examination is the role of pollutants, climate variables, and pathogens in contributing to complex disease dynamics and physiological disruptions, with particular emphasis on immune and endocrine functions. This research brings to light emerging evidence on the severe implications of environmental pressures on a variety of taxa, including predatory mammals, raptorial birds, seabirds, fish, and humans, which are pivotal as indicators of broader ecosystem health and stability. We delve into the nuanced interplay between environmental degradation and zoonotic diseases, highlighting novel intersections that pose significant risks to biodiversity and human populations. The review critically evaluates current methodologies and advances in understanding the morphological, histopathological, and biochemical responses of these organisms to environmental stressors. We discuss the implications of our findings for conservation strategies, advocating for a more integrated approach that incorporates the dynamics of zoonoses and pollution control. This synthesis not only contributes to the academic discourse but also aims to influence policy by aligning with the Global Goals for Sustainable Development. It underscores the urgent need for sustainable interactions between humans and their environments, which are critical for preserving biodiversity and ensuring global health security. By presenting a detailed analysis of the interdependencies between environmental stressors and biological health, this review highlights significant gaps in current research and provides a foundation for future studies aimed at mitigating these pressing issues. Our study is significant as it proposes integrative and actionable strategies to address the challenges at the intersection of environmental change and public health, marking a crucial step forward in planetary health science.

1. Introduction: the one and planetary health perspective

In an era where the impact of human activity on the natural environment has become unmistakably critical, the One and Planetary Health perspective emerges as a vital framework for understanding and addressing the interconnected health of people, animals, and ecosystems (Poitras, 2021; Adhikari and Halden, 2022; Joksimovic et al., 2022). This review rigorously examines the effects of environmental stressors such as pollution, climate change, and habitat destruction, which are increasingly disrupting the delicate balance of our ecosystems. As ecosystems falter under these stressors, the ripple effects on biodiversity and human communities become more pronounced, necessitating an urgent re-evaluation of our environmental policies and health practices (Crane et al., 2021; Xu et al., 2023; Anas et al., 2024; Saleem et al., 2024a). Moreover, this perspective facilitates the identification of proactive measures that can mitigate negative outcomes, promoting resilience across all forms of life (Masson et al., 2020; Kotcher et al., 2021; Nasibova et al., 2023). With a focus on the latest research from 2022 to 2024,

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we explore how these changes not only affect wildlife but also have profound implications for human health, as both are inextricably linked through shared environments and resources (Fagre et al., 2022; de Jersey et al., 2023; Verma et al., 2023b). The novelty of this review lies in its holistic approach, synthesizing current knowledge on the physiological and pathological responses of diverse species to environmental challenges, thereby providing a comprehensive perspective on the cascading effects on ecosystem health and human well-being.

The introduction of anthropogenic chemicals into ecosystems has led to widespread endocrine disruption among wildlife and humans, altering reproductive patterns and immune responses (Marlatt et al., 2022; Mfarrej et al., 2022). Concurrently, climate change is reshaping disease vectors and patterns, introducing new challenges in disease management across multiple species (Saleem et al., 2020d; Kotcher et al., 2021; León et al., 2023). This complex interplay between chemical exposure and climate effects underscores the necessity for integrated research approaches that span multiple disciplines (Lamb et al., 2022; Singh et al., 2023). As we gain deeper insights into these interactions, it becomes possible to develop more effective strategies for environmental management and health interventions (Mabrouk et al., 2023; Saleem et al., 2024b). Additionally, such a comprehensive understanding aids in forecasting future trends in health and disease, enabling preemptive actions to safeguard vulnerable populations and ecosystems (Collado-Mateo et al., 2021; Rehman et al., 2021; Rush et al., 2021; Sufyan et al., 2021). This review delves into the intricate web of relationships between these stressors and health, extending our analysis to include predatory mammals, birds, fish, and humans. Through a detailed examination of morphological, histopathological, and biochemical changes, we illuminate how alterations in one species can serve as indicators of broader ecological shifts. The importance of this review is underscored by its identification of significant gaps in current research and its proposal of novel integrative conservation strategies that align with global sustainability goals.

The objectives of this review are multifaceted: it aims not only to document the impacts of environmental stressors on immune and endocrine systems across species but also to highlight the importance of a One Health approach in addressing these challenges. We emphasize the interconnectedness of human, animal, and environmental health, exploring sustainable solutions such as pollution management, energy use, and biodiversity conservation. Ultimately, this review seeks to contribute to the broader literature advocating for a holistic approach to health and environmental policy, recognizing the complex web of connections that sustain life on our planet. The significance of our review lies in its potential to influence policy and practice, aiming to enhance global health security and ecosystem resilience through informed and actionable strategies. This review provides a foundational framework that can guide policymakers in crafting regulations and interventions that directly address the root causes of environmental and health challenges. By integrating the latest scientific findings into practical applications, our work supports the development of more sustainable practices that balance human needs with ecological preservation. Furthermore, the insights garnered from this work can serve as a crucial tool for educating stakeholders and the public about the critical linkages between environmental stewardship and health outcomes, fostering a more informed and engaged global community.

2. The impact of environmental chemicals on wildlife and human health

Environmental chemicals, which include both naturally occurring substances and those created by human activities, significantly influence the health of both wildlife and humans (Marlatt et al., 2022). These chemicals, pervasive in our environment, have sparked considerable worries about their capability to interfere with vital biological systems (Saleem et al., 2024b). Specifically, there is growing concern about their potential effects on the immune and endocrine systems, which play crucial roles in maintaining the health and balance of organisms (Al Sharabati et al., 2021). These disruptions can lead to a range of adverse health outcomes, from developmental abnormalities in wildlife to increased susceptibility to diseases in humans (Collier et al., 2022). The long-term exposure to these chemicals, even at low levels, can accumulate over time, leading to chronic health issues and affecting reproductive success in various species (Sánchez et al., 2020). This growing body of evidence underscores the need for more stringent regulation and monitoring of environmental chemicals to safeguard the health of both wildlife populations and human communities (Wilson et al., 2020).

2.1. Immune system disruption

The immune system, essential for the survival of all living organisms, is highly susceptible to disruption by environmental chemicals (Suzuki et al., 2020). These chemicals can interfere with the immune system at multiple levels, ranging from cellular components to the systemic immune response (Chiu et al., 2020). For instance, certain pesticides and industrial chemicals have been found to impair the function of white blood cells, which play a crucial role in fighting infections (Ebrahimi et al., 2020). This impairment can lead to an increased susceptibility to infectious diseases and can also affect the body's ability to fight off cancer cells (Burgos-Aceves et al., 2021).

Moreover, environmental chemicals can alter the production and function of cytokines, which are signaling molecules that mediate and regulate immunity, inflammation, and hematopoiesis (Vogel et al., 2020). Changes in cytokine levels can disrupt the delicate balance of the immune system, leading to either immunosuppression or, conversely, autoimmunity, where the body mistakenly attacks its own tissues (Celebi Sozener et al., 2022). In wildlife, this disruption can have far-reaching consequences, affecting not only individual animals but also entire populations (Lee et al., 2022). For example, immune system impairment in fish due to water pollution has been linked to population declines (Sueiro et al., 2020). Similarly, birds exposed to certain pesticides have shown weakened immune responses, making them more vulnerable to diseases that could affect their survival and reproduction (Moreau et al., 2022).

2.2. Endocrine system interference

The endocrine system, which regulates physiological processes through hormones, is another critical target of environmental chemicals (Guarnotta et al., 2022). Endocrine disruptors are chemicals that can interfere with the normal functioning of the hormonal system in both wildlife and humans (Yilmaz et al., 2020). These disruptors can mimic, block, or alter hormone levels, leading to a range of adverse health effects (Pironti et al., 2021). One of the most well-known impacts of endocrine disruptors is on reproductive health (Thambirajah et al., 2022). For instance, certain industrial chemicals have been linked to altered reproductive behaviors and decreased fertility in both animals and humans (Skakkebaek et al., 2022). In wildlife, this can lead to population declines and even local extinctions (Canipari et al., 2020). Endocrine disruptors can also affect the development of offspring, leading to birth defects, developmental disorders, and altered sex ratios (López-Rodríguez et al., 2021). Besides reproduction, endocrine disruptors can impact other physiological processes controlled by hormones, such as growth, metabolism, and behavior (Palanza et al., 2021). For example, chemicals that mimic or interfere with thyroid hormones can disrupt metabolic processes, leading to growth disorders in both wildlife and humans (Thambirajah et al., 2022).

The impacts of environmental chemicals on the immune and endocrine systems are of particular concern because they can have long-term and even transgenerational effects (Robaire et al., 2022). Chemical exposure during critical developmental periods can lead to health issues that manifest later in life or even in subsequent generations (Van Cauwenbergh et al., 2020). In summary, the impacts of environmental

chemicals on the immune and endocrine systems of wildlife and humans are profound and far-reaching. Understanding these impacts is crucial for developing strategies to mitigate their effects and protect the health of both wildlife and human populations. This requires a multidisciplinary approach, combining insights from environmental science, toxicology, biology, and medicine. By addressing these challenges, we can work towards a healthier and more sustainable future for all species sharing our planet. As shown in Fig. 1, the pathways of environmental chemicals from their sources to their health impacts highlight the pervasive nature of these substances.

3. Infectious diseases and climate change: a dual threat to biodiversity

The intricate relationship between infectious diseases and climate change represents a significant threat to global biodiversity, weaving a complex narrative of ecological imbalance and species vulnerability (Williams et al., 2021). As our planet undergoes rapid climatic shifts, the repercussions on disease dynamics and biodiversity are profound and multifaceted (Schmeller et al., 2020). These shifts lead to altered patterns of temperature and precipitation, which can expand the ranges of many pathogens and vectors, thereby exposing new populations and ecosystems to risk (Baker et al., 2022). The changing climate also stresses wildlife, potentially compromising immune systems and making species more susceptible to diseases that they once might have warded off (Wu et al., 2018). In addition, the disruption of traditional migration routes due to climate change can result in unusual contact between species, including humans, increasing the opportunity for cross-species transmission of infectious diseases (Williams et al., 2021). Phenomena such as ocean warming and acidification further compound these risks, as marine ecosystems and the species that depend on them face similar health challenges (Gao et al., 2017; Adnan et al., 2022). The loss of biodiversity due to disease can lead to reduced genetic diversity and weakened ecosystem services, which are vital for everything from clean water and air to pollination and soil fertility (Akram et al., 2023; Rasheed et al., 2023). The urgency to act is underscored by the potential for cascading effects, where the decline in one species can lead to unforeseen consequences throughout an ecosystem (Mfarrej et al., 2022). It is crucial that conservation and health strategies evolve in tandem with these changes, promoting resilience in both natural systems and the species that inhabit them (Yilmaz et al., 2020). By taking a proactive stance, bolstered by scientific research and cross-sector collaboration, there is a chance to mitigate these threats and preserve the delicate ecological balance upon which all life on earth depends.

Climate change, driven by anthropogenic activities, has led to altered weather patterns, rising temperatures, and shifting ecosystems (Jansson and Hofmockel, 2020). These environmental changes have a direct impact on the distribution and prevalence of infectious diseases (León et al., 2023). Warmer temperatures can extend the geographic range (Mobeen et al., 2021; Azeem et al., 2022; AL-Huqail et al., 2023) and seasonality of vectors such as mosquitoes and ticks, which carry diseases like malaria, Lyme disease, and West Nile virus (Boada et al., 2022). This expansion not only affects the health of human populations but also poses a serious risk to wildlife, altering the dynamics of existing ecosystems (Doney et al., 2020). Additionally, changes in precipitation patterns and humidity levels due to climate change can create favorable conditions for the proliferation of pathogens (Maja and Ayano, 2021). Increased rainfall and flooding, for example, can lead to higher incidences of waterborne diseases, affecting both terrestrial and aquatic species (Wu et al., 2018). Drought conditions, on the other hand, can

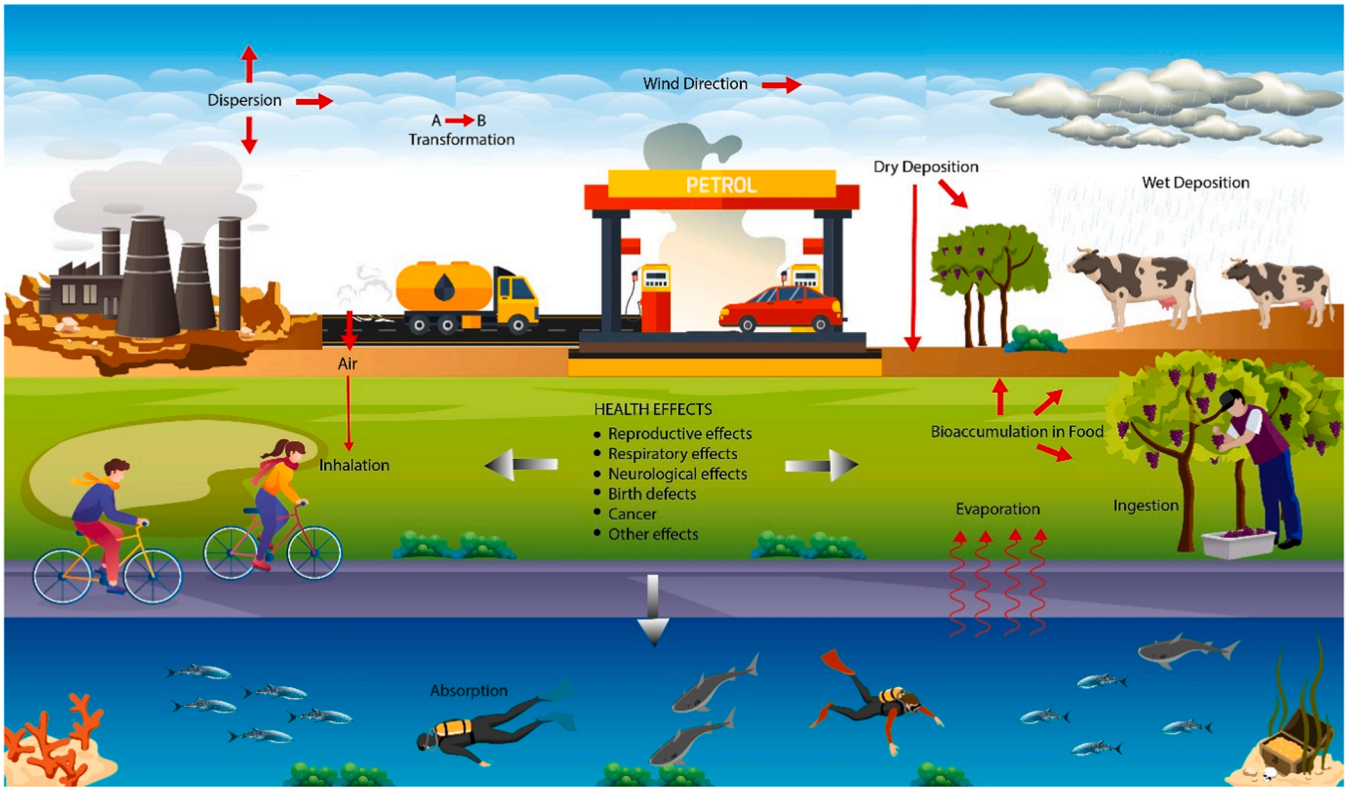

Fig. 1. Schematic representation of the transmission of environmental chemicals and their health impacts - This diagram illustrates the journey of environmental chemicals from their sources, such as industrial plants and petrol stations, through processes of dispersion and transformation. It shows how these chemicals enter the atmosphere, are subject to dry and wet deposition, and ultimately impact both terrestrial and aquatic ecosystems. The graphic highlights various routes of human exposure to these chemicals, including inhalation and ingestion, and notes the potential health effects such as reproductive and neurological effects, respiratory issues, birth defects, and cancer. The cycle of bioaccumulation in the food chain is also depicted, indicating how chemicals can concentrate in living organisms over time.

concentrate populations of animals around limited water sources, increasing the likelihood of disease transmission (Yasmin et al., 2021; Wahab et al., 2022; HUSSAIN et al., 2023).

The impact of climate change on infectious diseases is further complicated by its effects on biodiversity (Berrang-Ford et al., 2019). Species that are unable to adapt to rapid environmental changes may experience population declines or extinction, leading to a loss of biodiversity (Schmeller et al., 2020). This loss can have cascading effects, as healthy ecosystems typically function as natural controls for disease spread (Williams et al., 2021). A reduction in biodiversity can disrupt these controls, allowing for more frequent and severe outbreaks of infectious diseases (Weiskopf et al., 2020). In addition to altering the distribution and intensity of diseases, climate change can also impact the immune responses of various species (Poitras, 2021). Animals under stress from environmental changes may have weakened immune systems, making them more susceptible to infections (Maja and Ayano, 2021). This susceptibility is particularly concerning for species already at risk due to habitat loss, pollution, and other human-induced factors (Harkness et al., 2020).

The intersection of infectious diseases and climate change presents a formidable challenge to the conservation of biodiversity, necessitating a comprehensive and forward-thinking approach to safeguard our ecosystems (Williams et al., 2021). As climate change accelerates, it alters habitats and the distribution of species, which can in turn influence the emergence and spread of infectious diseases (Singh et al., 2020). This intricate dynamic calls for vigilant monitoring of disease vectors and ecological hotspots where outbreaks are more likely to occur (Hickmann et al., 2021). It is imperative to preserve the integrity of natural habitats, not only as a sanctuary for wildlife but also as a natural buffer against the spread of diseases (Xie et al., 2020). Furthermore, the restoration of degraded ecosystems can enhance natural resilience and provide a more stable environment for species to thrive, reducing the likelihood of disease transmission (Yeung et al., 2020). Strategies to reduce greenhouse gas emissions are also critical, as they directly contribute to slowing down the climate change process, thereby mitigating its impact on disease proliferation and biodiversity loss (Lamb et al., 2021). In facing this dual threat, it is clear that no single discipline can tackle the issue alone (Burton et al., 2022). An interdisciplinary collaboration is essential, drawing upon the collective expertise of ecologists who understand the complex relationships within ecosystems, epidemiologists who can trace and predict disease patterns, climate scientists who can forecast environmental changes, and conservation biologists who can develop and implement effective conservation strategies (Wen et al., 2018). Such a coalition allows for a holistic understanding of how climate-driven changes influence disease dynamics and the implications for biodiversity (Schmeller et al., 2020). Acknowledging the interconnectedness of climate, disease, and biodiversity is the first step towards developing integrated solutions (Weiskopf et al., 2020). By doing so, we open the door to innovative conservation strategies that are adaptable and robust enough to protect the health of our planet (Zhao et al., 2022). These strategies may include establishing early warning systems for disease outbreaks, promoting biodiversity as a means of disease regulation, and implementing policies that integrate biodiversity conservation into public health and land-use planning (Weiskopf et al., 2020). Through these concerted efforts, we can aspire to maintain the delicate balance of our ecosystems and ensure the survival of the rich tapestry of life that inhabits our planet (Coleine et al., 2022). As depicted in Fig. 2, the convergence of increased global connectivity, environmental

Fig. 2. The complex interplay between human activity, climate change, and infectious diseases - This figure maps the multifaceted links between urbanization, deforestation, global connectivity, and increased travel and trade with the emergence and spread of infectious diseases. It highlights how these factors contribute to the rise of pandemics and the spread of diseases like Dengue, Malaria, and Lyme disease. The central depiction of the Earth emphasizes the global scale of these issues, while the surrounding magnified lenses focus on specific contributing factors such as invasive vectors, extreme weather events, and changes in land use.

changes, and climate-related extreme weather events poses a significant threat to biodiversity, driving the spread of infectious diseases.

4. Wildlife as sentinels: studying predatory mammals, birds, and fish

In the realm of environmental monitoring and ecological research, wildlife species, particularly predatory mammals, birds, and fish, serve as vital sentinels (García-Fernández et al., 2020). These creatures, residing at the top of the food chain, provide crucial insights into the health of their ecosystems (Amadi et al., 2022). Through detailed analysis of their biological markers, researchers can detect early signs of environmental degradation, such as the presence of heavy metals or other contaminants (Andrews et al., 2023). By studying morphological and histopathological features, scientists can observe the direct effects of pollutants on individual organisms, including cellular damage and changes in tissue structures (Eötvös et al., 2020; Noor et al., 2021). Blood biochemistry and bone density, on the other hand, offer quantitative data that can be used to infer the physiological stress that these animals endure, which may be reflective of broader environmental issues (Brent et al., 2021). Such studies also aid in understanding the long-term consequences of bioaccumulation of toxins and the resultant biological magnification through the food web (Faisal et al., 2022). This sentinel role is particularly significant as these species often have wide-ranging habitats, meaning that their health can reflect the condition of extensive ecological zones (Newsom et al., 2023). Moreover, as many of these species are also of conservation concern, their monitoring not only informs us about environmental health but also about the effectiveness of current conservation efforts (Matuszewski et al., 2020). Furthermore, the decline in the health of these sentinel species can signal disruptions in the ecosystem services they provide, such as pest control and carrion disposal, which are essential for maintaining ecological balance (Facca et al., 2020). By keeping a close watch on these indicators, ecologists and conservationists can devise more effective strategies to preserve biodiversity and ensure the sustainability of natural resources (Somaweera et al., 2020).

4.1. Morphological and histopathological insights

Morphological studies in wildlife, focusing on the structure and form of organisms, offer valuable information about the impacts of environmental stressors (Jenkins et al., 2021). Changes in morphology, such as variations in size, shape, or coloration, can indicate exposure to pollutants, nutritional deficiencies, or other environmental challenges (Berlow et al., 2021). For instance, deformities in birds' beaks or fish fins have been linked to chemical contaminations in their habitats (Johnson et al., 2020). Such aberrations can often be the first visible signs that an ecosystem is being compromised by anthropogenic activities (Ghaffar et al., 2020). By tracking these morphological changes, researchers can establish a correlation between the degree of alteration in physical traits and the intensity or type of environmental pressure (Wallace et al., 2020). This approach has been instrumental in identifying the sub-lethal effects of toxins that might not immediately result in mortality but can significantly impair the survival and reproductive success of wildlife species (Córdoba-Tovar et al., 2022). Furthermore, these studies can serve as a basis for regulatory measures to control the release of harmful substances into the environment, aiming to prevent genetic or physiological damage to wildlife (Saleem et al., 2020a; Brandts et al., 2022). Hence, morphological analysis is a crucial component of ecological assessment, providing tangible evidence of the subtle yet profound effects of human impact on nature (Nienhuis et al., 2020).

Histopathology, the microscopic examination of tissues to study the manifestations of disease, is another powerful tool (Vasquez-Bonilla et al., 2020). It allows for the detection of cellular-level changes that may not be visible externally (Bradley et al., 2020). For predatory mammals, birds, and fish, histopathological examinations can reveal tissue damage caused by pollutants, signs of infectious diseases, or physiological changes due to climate change (Suh et al., 2021). This kind of analysis is particularly important in understanding the sub-lethal effects of environmental toxins, which may not immediately result in death but can significantly impact health and reproductive success (Bösmüller et al., 2020). Furthermore, histopathological techniques can uncover the cumulative effects of stressors over time, offering a retrospective window into an organism's exposure history to various environmental pressures (El Hachem et al., 2020). These insights are critical for conservation efforts, as they help in pinpointing specific threats to wildlife populations and in developing targeted interventions to mitigate these risks (Calabrese et al., 2020).

4.2. Blood biochemistry and bone density analyses

The analysis of blood biochemistry in wildlife provides a window into their physiological health (Esmaeili, 2021). Blood tests can reveal a range of information, including nutritional status, exposure to toxins, and the presence of infectious diseases (Harsij et al., 2020). For example, elevated levels of certain enzymes can indicate liver or kidney damage due to toxin exposure (Alagawany et al., 2021). Similarly, changes in hormone levels can be indicative of stress or endocrine disruption (Ronaldson and Davis, 2020). Additionally, by monitoring changes in blood biochemistry over time, researchers can discern patterns that signal the onset of diseases or the effects of long-term exposure to environmental changes (Sula et al., 2020). This type of data is invaluable for the implementation of timely conservation measures and for assessing the efficacy of habitat restoration efforts (Liu et al., 2020). It also provides essential baseline information that can be used to gauge the resilience of wildlife populations to future environmental stressors (Bhandari et al., 2020).

Bone density studies in wildlife are especially relevant for assessing long-term exposure to environmental stressors, such as heavy metals (Vilela et al., 2020). Predatory animals, which are often at the end of the food chain, can accumulate significant levels of these toxins over time (McIlwraith et al., 2021). Reduced bone density can indicate heavy metal poisoning or deficiencies in essential nutrients caused by environmental degradation (Zhang et al., 2020). In summary, the study of predatory mammals, birds, and fish offers essential insights into the health of ecosystems. By examining morphological and histopathological features, as well as conducting blood biochemistry and bone density analyses, researchers can detect early signs of environmental distress. This knowledge not only aids in the conservation of these sentinel species but also provides critical information for the protection of biodiversity and the maintenance of healthy ecosystems (Verma et al., 2023a). These multifaceted studies form a comprehensive approach to wildlife conservation, enabling a deeper understanding of how anthropogenic factors affect animal health and, by extension, ecosystem integrity (Singh et al., 2023). The data derived from such research can guide policy decisions and inform public awareness about the importance of reducing environmental contaminants (Ma et al., 2021). Ultimately, the health of these top predators is a barometer for the overall well-being of our natural world, signalling when human activities have tipped the balance and when immediate corrective action is necessary (Jalili et al., 2020).

5. Human-wildlife interactions: zoonoses and ecosystem services

The intersection of human and wildlife domains has profound implications, particularly in the context of zoonoses and the provision of ecosystem services (Everard et al., 2020). Zoonoses, diseases that can be transmitted from animals to humans, are a critical public health concern, often exacerbated by increased contact between humans and wildlife (Ratnadass and Deguine, 2021). This interaction is a double-edged sword, where the rich biodiversity that supports

ecosystem services also poses risks for zoonotic disease transmission (Rush et al., 2021). Ecosystem services, the benefits humans derive from nature, include provisioning services like food and water; regulating services such as disease control and climate regulation; supporting services like nutrient cycles; and cultural services that provide recreational, aesthetic, and spiritual benefits (Mubareka et al., 2023). Wildlife plays a crucial role in these services, maintaining ecological balance and functional ecosystems (Marlatt et al., 2022). However, when ecosystems are disrupted, whether through habitat loss, climate change, or other anthropogenic activities, the risk of zoonotic diseases can increase (Bertram et al., 2022). The intricate balance maintained by wildlife within these ecosystems is therefore essential not only for ecological health but also for human health, highlighting the need for an integrated One Health approach that recognizes the interdependence of people, animals, plants, and their shared environment (De Silva et al., 2021). As human activities continue to encroach upon natural habitats, it is imperative to implement sustainable practices that minimize habitat destruction and mitigate the risk of zoonotic spillover, thereby protecting both biodiversity and human societies from the far-reaching impacts of emerging infectious diseases (Sánchez et al., 2020; Andrews et al., 2023).

The loss of natural habitats often forces wildlife into closer proximity with human settlements, increasing the likelihood of disease transmission (Barbier, 2021). Deforestation and land-use changes, for instance, can displace animal populations and disrupt ecological balances, creating conditions where zoonoses can thrive (Tazerji et al., 2022). Additionally, climate change can alter the distribution of both wildlife and disease vectors, expanding the range of some zoonotic diseases (Rupasinghe et al., 2022). Conversely, healthy ecosystems can act as a buffer to disease transmission (Leal Filho et al., 2022). Biodiverse environments often contain a variety of species, some of which can act as 'dead-end' hosts, limiting the spread of pathogens (Rahman et al., 2020). Maintaining biodiversity is therefore crucial not only for the continued provision of ecosystem services but also for reducing the risk of zoonotic diseases (Keesing and Ostfeld, 2021). The conservation of natural habitats is thus not only an environmental or ecological imperative but a public health priority as well (Othman et al., 2022). By safeguarding biodiversity and ecosystem integrity, we can enhance natural disease regulation mechanisms that suppress the outbreak and spread of infectious diseases (Keesing and Ostfeld, 2021). It becomes clear that the health of human populations is inextricably linked to the health of wildlife and the environments they inhabit, underscoring the importance of holistic and cross-disciplinary approaches to land management and disease prevention (Williams et al., 2021).

Moreover, wildlife monitoring and conservation efforts play a significant role in predicting and preventing zoonotic outbreaks (Keatts et al., 2021). By understanding wildlife health and ecology, scientists can identify potential disease hotspots and implement measures to mitigate risks (Bernstein et al., 2022). This includes monitoring wildlife trade, as the movement of animals can facilitate the spread of pathogens across borders (Harrison et al., 2020). Strategic surveillance and regulation of wildlife markets, where a high diversity of species are often in close contact, is critical for early detection and control of zoonotic diseases (Ferreira et al., 2021). Education and awareness campaigns can also empower communities to adopt practices that reduce the risk of pathogen transmission from wildlife to humans (Petrovan et al., 2021). Furthermore, by investing in wildlife health research, we can develop a proactive rather than reactive approach to zoonotic diseases, enhancing global health security and maintaining the delicate balance of our planet's ecosystems (Magouras et al., 2020). In summary, the relationship between humans and wildlife is intricate and multifaceted, impacting both ecosystem services and the transmission of zoonotic diseases. A balanced approach that respects and maintains ecological integrity while managing wildlife populations is essential. This requires a collaborative effort involving public health, wildlife management, and environmental conservation sectors. By prioritizing ecosystem health, we can safeguard not only the invaluable services provided by nature but also protect against the emergence and spread of zoonotic diseases. The diverse impacts of human-wildlife interactions, ranging from road accidents involving wildlife to the implications of urban expansion on zoonotic disease risks, are depicted in Fig. 3.

6. Technological interventions in wildlife research: benefits and concerns

Technological advancements have significantly enhanced our capacity to study wildlife, offering new insights into the behaviors, physiological processes, and ecological dynamics of animals (Karthick et al., 2020). Key among these technological tools are satellite transmitters, which allow for the tracking of animal movements across vast distances, and immobilization techniques, which enable close-up study and medical interventions (Petso et al., 2022). These methods have yielded a wealth of data that was previously inaccessible, opening up new avenues for conservation and research (Stephenson, 2020). However, they also bring with them particular challenges, such as the need to ensure minimal stress and harm to the animals involved (Lahoz-Monfort and Magrath, 2021). Ethical considerations must be carefully weighed, ensuring that the welfare of the animals takes precedence in the pursuit of scientific knowledge (Hohenlohe et al., 2021). As we deploy these technologies, it is essential to maintain a balance between the acquisition of valuable ecological data and the responsibility to treat wildlife with respect and care (Caravaggi et al., 2020).

6.1. Satellite transmitters

The use of satellite transmitters has been a game-changer in wildlife research, offering an unprecedented ability to track and monitor animals over extensive areas (Craighead and Dunstan, 2024). These devices provide essential data on the movement patterns, habitat preferences, and population dynamics of various species, which are critical for effective conservation planning (Shuert et al., 2021). By utilizing this technology, researchers can pinpoint key habitats and migration routes, assess the impacts of environmental changes, and develop strategies to protect endangered species and preserve biodiversity (Lennox et al., 2020). Additionally, satellite transmitters have opened up new possibilities in behavioral ecology, allowing scientists to observe the intricacies of social structures, foraging strategies, and reproductive activities in a non-intrusive manner (Duggan et al., 2020). These insights are invaluable for understanding how animals interact with their environment and with each other, shedding light on complex ecological processes (Hui et al., 2021). However, the deployment of satellite transmitters is not without its concerns (Foley and Sillero-Zubiri, 2020). The attachment of these devices, if not done correctly, can lead to stress, injury, or even the death of animals (Washburn et al., 2022). Researchers are thus continually seeking methods that are less invasive and ensuring that the size and weight of the transmitters are proportionate to the animal's body to minimize impact (Lahoz-Monfort and Magrath, 2021).

Moreover, the reliability of the data collected can sometimes be compromised due to technical malfunctions or environmental obstacles that interfere with signal transmission (Robinson et al., 2021). This necessitates the development of more robust technology and backup systems to ensure consistent and accurate data collection (Barkley et al., 2020). Ethical considerations also come to the forefront with the use of satellite transmitters. The intervention in animals' lives must be justified by the potential conservation benefits (Chung et al., 2021). There is an ongoing debate about the extent to which tracking may inadvertently increase the risks animals face from predators or poachers (Heggøy et al., 2021). Ethical frameworks and regulatory guidelines are crucial to govern the use of such technology, ensuring that research does not compromise the welfare of the subjects or the integrity of the ecosystems they inhabit (Ramesh et al., 2021). In expanding the use of satellite

Fig. 3. Human-Wildlife conflicts and their implications - This illustration showcases various scenarios where human activities intersect with wildlife habitats, leading to conflicts. It depicts deer-vehicle collisions as an increasing trend in North America, crop raiding by elephants as a source of food insecurity in vulnerable communities, urban rats acting as reservoirs for zoonotic diseases due to inadequate infrastructure, and the impact of marine predators on fisheries contributing to socioeconomic challenges. Each scene highlights a unique set of issues arising from the close quarters shared by humans and wildlife.

transmitters, it is imperative that we strike a balance between technological advancement and ethical responsibility (Sergio et al., 2019). Each research project must be evaluated on a case-by-case basis, weighing the potential benefits against the risks involved, with the overarching goal of enhancing our understanding and protection of the natural world (Hofman et al., 2019).

6.2. *Immobilization techniques*

Immobilization techniques have become an invaluable tool in the field of wildlife conservation and research (Becciolini et al., 2019). They allow for direct interaction with animals, which is crucial for conducting detailed health assessments, administering medical treatments, and controlling diseases that could devastate populations (Kluyber et al., 2021). Additionally, these techniques provide a means to safely collect biological samples, such as blood or tissue, which are indispensable for a wide array of scientific investigations, including genetic studies and disease diagnostics (Zemanova, 2020). In the realm of conservation management, immobilization plays a pivotal role in translocating animals, whether it's for the purpose of diversifying genetic pools, reintroducing species into their native habitats, or rescuing them from areas where they face imminent threats (Tauqeer et al., 2021). The ability to handle wild animals safely is essential for these sensitive and often crucial interventions (Kunapongkiti et al., 2020). However, the process of immobilization is not without its drawbacks. The use of sedatives and other immobilization agents can introduce health risks, and the potential for adverse reactions like respiratory or cardiac distress necessitates a careful evaluation of drug types, dosages, and their administration (Anastas et al., 2021). The precision of this practice is of utmost importance and relies on continuous advancements in veterinary pharmacology (Rosner and Clark, 2021).

The stress induced by immobilization can be considerable, leading to potential behavioral changes that may disrupt the social structures of animal populations (Budžaki et al., 2022). The psychological impact on animals, both in the short and long term, must be a factor in the decision-making process when planning such interventions (Bouabidi et al., 2019). Additionally, there is a small but significant risk of mortality associated with immobilization, which underscores the need for such procedures to be carried out by experienced and highly trained personnel (Almeida et al., 2021). The development and adherence to stringent protocols are necessary to minimize risks and ensure animal safety. In summation, while the benefits of immobilization techniques in wildlife research are numerous, they carry inherent risks that must be carefully managed. The ethical implications of these interventions compel us to maintain a delicate balance between the pursuit of scientific knowledge and the well-being of the animals we study. It is the responsibility of the scientific community to ensure that these techniques are continuously refined and ethically justified, safeguarding the welfare of wildlife while advancing the cause of conservation and research. The integrative model shown in Fig. 4 captures the essence of modern wildlife research, characterized by its technological sophistication and collaborative nature.

7. Sustainability and the global goals: energy, pollution, and recycling

The SDGs act as a global call to action, targeting not only environmental stewardship but also poverty alleviation, economic growth, and social inclusion (Arora and Mishra, 2019). Energy initiatives, such as the transition to renewable sources, play a critical role in reducing the carbon footprint, while efforts in pollution reduction and recycling are essential for conserving natural resources and reducing ecological degradation (Lee et al., 2020). Furthermore, these goals emphasize the interconnectedness of human activities and the natural environment, promoting practices that ensure the long-term health and viability of both. Collectively, the pursuit of these objectives is integral to fostering resilient communities and ecosystems capable of withstanding and adapting to the challenges of climate change and resource scarcity (Mazhar et al., 2021).

Fig. 4. Integrative model of technological interventions in wildlife research - This diagram illustrates the collaborative network between various stakeholders in wildlife research facilitated by technology. It highlights the flow of information and resources among biologists, community scientists, computer vision researchers, data scientists, and intelligent AI agents. The interconnectedness underscores the use of social networks for data gathering and sharing, the role of data management and image analysis servers in processing information, and the contribution of diverse research disciplines in enhancing our understanding of wildlife.

7.1. Energy

The transition to sustainable energy is a cornerstone of the SDGs, particularly Goal 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all (Santika et al., 2020). The challenge lies in shifting from fossil fuel-based energy systems, which are major contributors to greenhouse gas emissions and climate change, to renewable and clean energy sources such as solar, wind, hydro, and geothermal (Kong'ani et al., 2021; Lamb et al., 2021). The integration of these renewable energy sources into national grids, the development of storage technologies, and investments in smart grid technologies are essential steps towards a sustainable energy future (Majid, 2020). Equally important is the need to improve energy efficiency in various sectors including industrial processes, building design, and transportation (Qazi et al., 2019). This not only reduces the overall energy demand but also cuts down on emissions and costs (Østergaard et al., 2020). Advancing toward this sustainable energy future also requires substantial financial and policy support from governments and private sectors worldwide (Polzin et al., 2019). It involves incentivizing clean energy solutions and phasing out subsidies for fossil fuels to encourage the adoption of renewables (Lu et al., 2020). Furthermore, education and capacity-building initiatives are vital to prepare workforces for the new green economy, ensuring that the transition to sustainable energy creates jobs and promotes social equity (Taghizadeh-Hesary and Yoshino, 2020). International cooperation and technology transfer between nations are equally crucial to ensure that all countries, regardless of their economic status, can access the benefits of sustainable energy technologies (Sachs et al., 2019).

7.2. Pollution

Addressing pollution in all its forms - air, water, soil, and noise - is critical to achieving several SDGs, particularly Goal 3 (good health and well-being), Goal 6 (clean water and sanitation), and Goal 11 (sustainable cities and communities) (Guppy et al., 2019). Air pollution, largely from industrial emissions and vehicle exhaust, poses a significant risk to human health and the environment (Mumtaz et al., 2021). Strategies to combat air pollution include adopting cleaner production methods, enhancing public transportation systems, and increasing green spaces in urban areas (Singh et al., 2020). Water pollution, caused by industrial discharges, agricultural runoff, and inadequate wastewater management, threatens ecosystems and public health (Zaheer et al., 2020a; Chai et al., 2021; Hashmat et al., 2021). Efforts to combat water pollution include implementing stringent effluent treatment norms, promoting sustainable agricultural practices, and improving sewage treatment infrastructure (Hashem et al., 2020; Zaheer et al., 2020b; Parde and Behera, 2023; Wahab et al., 2023). Soil pollution, often overlooked, affects food safety and ecosystem health (Rehman et al., 2020; Saleem et al., 2020c; Alatawi et al., 2022; Dominic et al., 2022; Nawaz et al., 2024). Measures to address soil pollution include proper waste disposal, controlling the use of hazardous chemicals in agriculture, and remediating contaminated sites (Parveen et al., 2020; Saleem et al., 2020b; Zaheer et al., 2020a; Ma et al., 2022). In addition, noise pollution, emerging as an environmental concern, impacts both wildlife and human health, necessitating the enforcement of noise control regulations and urban planning that incorporates quiet zones (Farooqi et al., 2020). Cross-sectoral policies and integrated management systems are also paramount in addressing the multispectral nature of pollution, ensuring that efforts to clean the air do not inadvertently lead to

increased water or soil contamination (Yang et al., 2020).

7.3. Recycling

Recycling is a key aspect of sustainable waste management, aligning with SDG 12 (responsible consumption and production) (He et al., 2022). Effective recycling reduces reliance on raw materials, minimizes waste, lowers greenhouse gas emissions, and conserves energy (Oliveira et al., 2020). To enhance recycling rates, it is essential to establish efficient collection systems, encourage public participation, and invest in recycling facilities (Wang et al., 2022). Furthermore, promoting the design of products for easy disassembly and recycling at the end of their life cycle is crucial (Zhao et al., 2022). Governments and industries need to foster a circular economy where products and materials are reused and recycled to the maximum extent, reducing the environmental footprint. Innovations in recycling technologies, including advanced sorting and processing techniques, can significantly improve the purity and quality of recycled materials, making them more competitive with virgin resources (Zhang et al., 2019). Additionally, creating economic incentives for both consumers and manufacturers to engage in recycling can accelerate the shift towards more sustainable consumption patterns and help achieve the ambitious targets of SDG 12 (Krauklis et al., 2021).

In summary, the interdependence of energy, pollution, and recycling in the context of the SDGs highlights the need for an integrated approach to sustainability. This involves coordinated actions from governments, businesses, civil society, and individuals. Embracing renewable energy, combating pollution, and enhancing recycling are not just environmental imperatives but also opportunities for economic growth and social development. By addressing these challenges, we can progress towards a more sustainable, equitable, and prosperous future for all. As illustrated in Fig. 5, the Sustainable Development Goals represent a holistic approach to addressing global challenges across social, economic, and environmental dimensions.

8. Strengths and limitations

8.1. Strengths of the review

8.1.1. Comprehensive scope and integration

One of the major strengths of this review is its broad scope, encompassing a diverse array of environmental stressors and their impacts on both wildlife and human health. The review integrates multiple dimensions of environmental science, ecology, public health, and policy analysis, providing a holistic view of the subject matter. By synthesizing findings from various disciplines, we offer a nuanced understanding of how anthropogenic chemicals, climate change, and other environmental factors interact with biological systems. This integrated approach is crucial for developing comprehensive strategies to mitigate the adverse effects of these stressors.

8.1.2. Up-to-date and relevant literature

Our review is grounded in the most recent literature, incorporating studies from the last three years that reflect the current state of knowledge in the field. This ensures that the conclusions and recommendations are based on the latest scientific evidence, making them relevant and timely for both researchers and policymakers. The inclusion of recent publications allows us to present new insights that have emerged in response to rapidly changing environmental conditions and advances in technology.

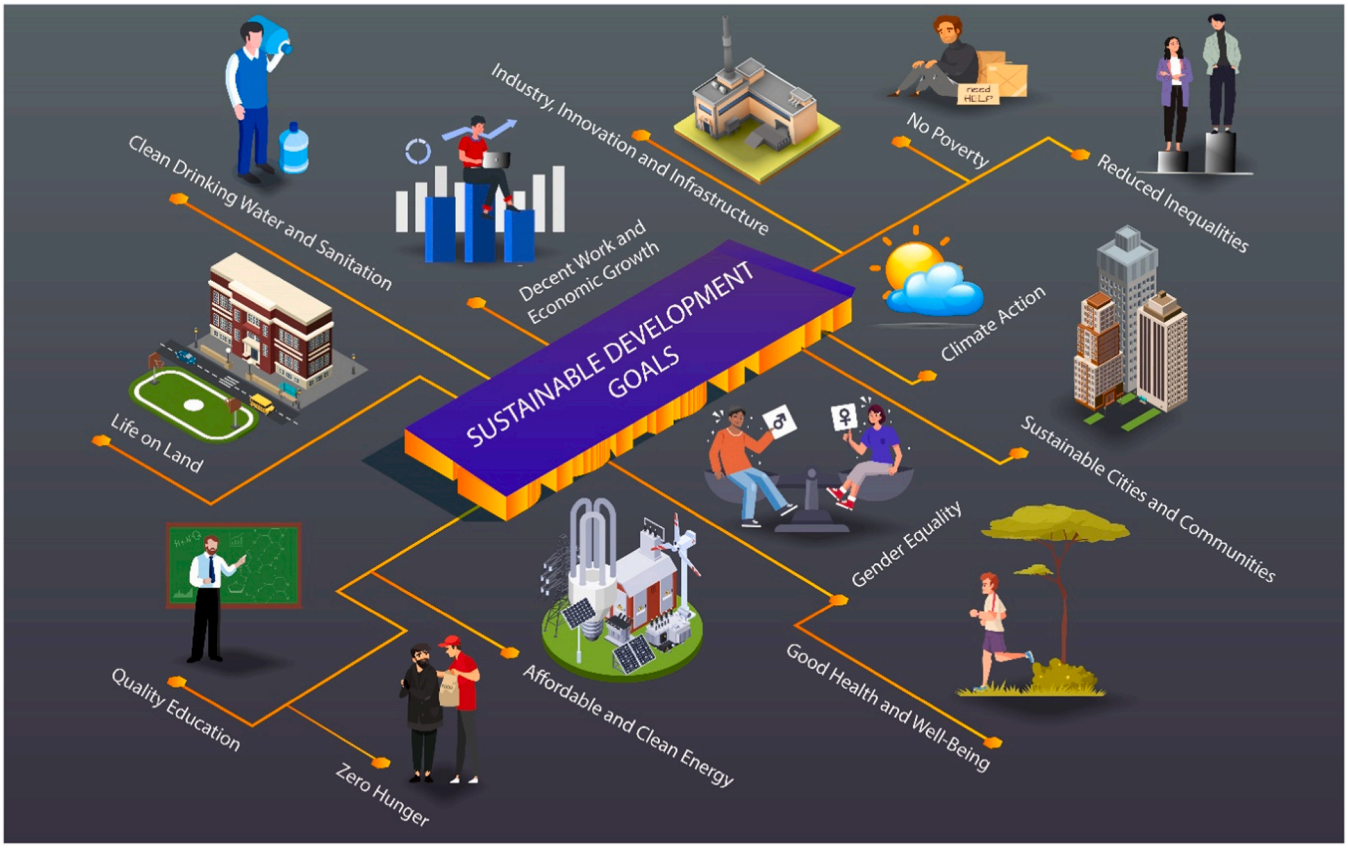

Fig. 5. Visual overview of the United Nations SDGs - This illustrative graphic provides a snapshot of the various SDGs set by the United Nations, depicting their interconnected nature and global impact. Each icon represents a specific goal, such as 'No Poverty', 'Quality Education', and 'Clean Water and Sanitation', highlighting the diverse areas of focus that collectively contribute to sustainable development. The central positioning of the SDGs reflects their role as the guiding framework for international efforts towards a more equitable, healthy, and sustainable future.

8.1.3. Global perspective

The review addresses the global nature of environmental challenges, discussing cases and studies from various countries and regions. This global perspective is essential for understanding the widespread impacts of environmental stressors and for fostering international cooperation in environmental management and health practices. By examining the issue from a global standpoint, we can better appreciate the scale of the challenges and the need for coordinated international responses.

8.1.4. Policy-oriented recommendations

A significant strength of this review is its focus on practical and policy-oriented recommendations. The conclusions drawn from the literature are translated into actionable strategies that can be implemented by governments, organizations, and communities. These recommendations are designed to be feasible and effective, tailored to the specific challenges identified in the review. The emphasis on policy implications makes the findings particularly valuable for decision-makers looking to address environmental and health issues in a systematic manner.

8.2. Limitations of the review

8.2.1. Variability in study quality and methodologies

Despite the comprehensive nature of the literature reviewed, there is significant variability in the quality and methodologies of the studies included. This variability can affect the robustness of the conclusions drawn. Different studies may use different metrics, samples, or analytical methods, which can lead to inconsistencies in the data and potentially affect the overall synthesis of findings. While we have made efforts to critically evaluate the quality of the studies, the inherent variability is a limitation that must be acknowledged.

8.2.2. Geographical and cultural bias

While the review aims to be global in scope, there remains a bias towards studies conducted in Western countries, where research funding and publication rates are typically higher. This bias can skew the understanding of environmental impacts, as the conditions, cultural practices, and policy environments in less-studied regions may differ significantly. Future reviews would benefit from a more balanced representation of studies from diverse geographical and cultural contexts.

8.2.3. Temporal limitations

The focus on recent literature, while beneficial for providing timely insights, also means that the review may not fully capture long-term trends and outcomes. Environmental and health impacts often manifest over long periods, and recent studies may not yet be able to fully document these effects. Additionally, the rapidly evolving nature of environmental science means that newer studies could soon supersede the findings discussed.

8.2.4. Potential for interdisciplinary gaps

While the review integrates knowledge from various disciplines, there are inherent challenges in achieving a truly interdisciplinary approach. Different fields may use different terminologies, frameworks, and perspectives, which can lead to gaps in integration. These gaps might hinder the comprehensive understanding of how environmental stressors interplay with human and wildlife health. Greater collaboration across disciplines would help to minimize these gaps and enhance the interdisciplinary nature of the review.

In sum, this review provides a comprehensive analysis of the impacts of environmental stressors on wildlife and human health, offering valuable insights and actionable recommendations. However, the strengths of the review must be viewed in light of its limitations, including variability in study methodologies, geographical biases, temporal constraints, and potential interdisciplinary gaps. Recognizing these limitations is crucial for accurately interpreting the findings and for guiding future research and policy efforts. This balanced view will enhance the credibility of the review and support the development of more effective environmental and health strategies.

9. Conclusion

9.1. Integrating wildlife and human health for a sustainable future

The intricate interplay between wildlife and human health is more than a mere aspect of ecological concern; it is pivotal to our ongoing quest for sustainability. As our review has demonstrated, the health of our planet and all its inhabitants—human and non-human—are profoundly interconnected. Through this comprehensive examination, we have unearthed a multifaceted view of how environmental chemicals, climate change, disease dynamics, and human-wildlife interactions weave together to form a complex tapestry that affects global health and ecological balance.

9.2. Broad themes and major insights

Environmental chemicals:

Our analysis highlighted the profound impact of pollutants on biological health, causing significant disruptions in immune and endocrine systems across various species. This review has shown that the threat from these chemicals is not localized but has a global reach affecting diverse ecosystems and populations.

9.2.1. Climate change and infectious diseases

We found that climate change acts not only as a direct stressor on ecological and human health but also as a potent amplifier of disease spread, particularly zoonotic diseases. These findings underscore the need for proactive global health strategies that anticipate and mitigate the effects of climatic changes.

9.2.2. Wildlife as sentinels

Our study reinforced the role of wildlife in signaling ecological and health threats. Technological advancements have enabled more precise monitoring of wildlife health, providing essential data that can forecast potential environmental crises.

9.2.3. Human-wildlife interactions

Increasing encroachment into natural habitats has escalated the frequency and intensity of human-wildlife interactions, heightening the risk of zoonotic disease transmission and other health complications. Our review suggests that managing these interactions is critical for disease prevention and biodiversity conservation.

Sustainability and global goals:

The interdependencies identified in this review align closely with the Sustainable Development Goals set by the United Nations. Each insight from our study points to the necessity of integrated approaches that balance environmental stewardship with health and economic considerations.

9.3. Moving forward: a path toward sustainability

To navigate the complexities discussed, a multifaceted strategy is required—one that transcends traditional disciplinary boundaries and integrates diverse fields such as ecology, public health, and policy-making. Our conclusions suggest several future directions:

9.3.1. Interdisciplinary collaboration

Enhanced cooperation between scientists, healthcare professionals, and policymakers is essential to address the environmental challenges that directly impact public health.

9.3.2. Policy and decision making

Effective policies must reflect an understanding of the ecological bases of health and incorporate scientific insights into practical governance strategies. This approach can facilitate more resilient health and environmental systems.

9.3.3. Community engagement and education

Educating communities about the environmental determinants of health and engaging them in sustainable practices are crucial for long-term success. Community-driven initiatives can lead to more sustainable local and global outcomes.

9.3.4. Innovative research and technologies

Continued investment in research is vital. New technologies that monitor and mitigate the impacts of environmental stressors on wildlife and human health can lead to significant breakthroughs.

9.4. Summary and final thoughts

Our extensive review underscores the pivotal role of environmental stressors not only in affecting the health of wildlife and humans but also in shaping the future of our planet's ecosystems. By thoroughly examining the impacts of pollutants, climate change, and infectious diseases, we have identified critical linkages that demand an integrated approach for effective management and mitigation.

9.4.1. Understanding complex interactions

The evidence gathered highlights how interactions between environmental factors and biological responses are complex and multifaceted. These interactions influence a wide range of health outcomes in both wildlife and humans, suggesting that health cannot be compartmentalized but is a reflection of the broader environmental health.

9.4.2. Actionable strategies for mitigation

We propose several actionable strategies that are crucial for mitigating the adverse effects of environmental stressors. These include enhancing pollution controls, improving waste management, adopting sustainable agricultural practices, and enforcing legislation to protect natural habitats. These strategies are not only vital for reducing the immediate impact of environmental stressors but also for setting a sustainable path forward.

9.4.3. Policy integration and research implications

A significant finding from our review is the urgent need for policy frameworks that integrate the interdependencies between environmental and health sectors**.** Policies need to be informed by scientific research that elucidates the connections between environmental changes and health outcomes. Additionally, there is a need for continued research that fills the existing gaps in our understanding of these complex interactions.

9.4.4. The role of technological innovations

The deployment of new technologies in monitoring environmental health and detecting early signs of ecosystem distress can provide critical data that inform both research and policy. Technologies such as satellite imaging, bioinformatics, and advanced modeling techniques will be instrumental in predicting outcomes and formulating strategies to address them.

9.4.5. Education and community involvement

Educating the public and involving communities in environmental conservation are essential for the sustainability of health interventions. Awareness programs that illustrate the impact of environmental health on personal well-being can motivate individuals and communities to adopt more sustainable lifestyles**.**

9.4.6. Global cooperation and sustainability goals

Our findings emphasize the importance of global cooperation in addressing environmental challenges. The interlinked nature of environmental issues, transcending national borders, calls for collaborative efforts that align with global sustainability goals. This involves sharing knowledge, resources, and strategies to tackle common threats and work towards shared goals.

9.4.7. Ethical considerations and future directions

Ethical considerations in handling wildlife, employing new technologies, and implementing health interventions must be prioritized to ensure that efforts to mitigate environmental stressors do not inadvertently cause harm. Looking forward, research should also explore innovative ways to reverse the damage already done to ecosystems, potentially through restoration ecology and bioremediation techniques.

9.4.8. Long-term vision for a sustainable future

Ultimately, this review serves as a call to action for a concerted and unified approach to understanding and managing the interplay between environmental stressors and health. It is imperative that the insights gained are translated into effective strategies that protect and preserve the intricate web of life sustaining our planet. Our collective efforts must aim not just at mitigating current challenges but also at ensuring the long-term health and prosperity of all species, securing a viable and flourishing future for the generations to come.

CRediT authorship contribution statement

Jing Ma: Visualization, Validation, Software. **Feifei Jiang:** Writing – review & editing, Visualization, Software, Resources. **Mohammed A Alghamdi:** Writing – review & editing, Validation, Software, Resources. **Jean Wan Hong Yong:** Writing – review & editing, Writing – original draft, Software, Resources, Funding acquisition. **Yanfeng Zhu:** Validation, Supervision, Software. **Fu Chen:** Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

We, the authors of this review, hereby declare that there are no financial or non-financial conflicts of interest related to the content of this manuscript. Our work has been conducted and presented with full academic integrity, free from any undisclosed influences or conflicts that could affect the objectivity or credibility of our research and findings.

Data Availability

No data was used for the research described in the article.

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