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Review

Understanding Environmental Contamination Through the Lens of the Peregrine Falcon (*Falco peregrinus*)

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Abstract: The peregrine falcon (*Falco peregrinus*) stands out as a crucial sentinel species for assessing environmental contamination, owing to its widespread distribution, high position in the food chain, and susceptibility to pollutants. As apex predators, these remarkable birds accumulate various contaminants found in their prey, thus serving as valuable indicators of ecological health. The historical application of organochlorine pesticides, such as DDT, resulted in alarming population declines, highlighting the significant vulnerability of peregrines to environmental hazards. Recent research has shed light on the detrimental effects of heavy metal exposure, revealing critical health risks including compromised immune function and reduced reproductive success, which further highlight the ecological consequences of pollution for top predators. Moreover, the complex nature of brominated flame retardants poses challenges in balancing fire safety with environmental health, as these chemicals persist in the ecosystem and threaten peregrine falcon populations. In the future, the use of possible new bioindicators of environmental pollution opens up interesting prospects. This innovative approach may enhance our understanding of how contaminants affect reproductive health and contribute to a broader One Health perspective, emphasizing the interconnectedness of wildlife, human health, and ecosystem integrity. This comprehensive overview underscores the urgency of ongoing monitoring and regulatory efforts to protect peregrine falcons and, by extension, our shared environment.

Keywords: environmental pollution; sentinel; peregrine falcon; raptors; heavy metals; organochlorine pesticides; DDT; dieldrin; brominated flame retardants; One Health

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1. Introduction

Environmental pollutants, whether of natural origin or the result of human activity, pose significant threats to the health of both organisms and ecosystems. Some pollutants, such as legacy chemicals like dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs), have been present in the environment for decades. Despite being banned or restricted in many parts of the world, these substances continue to persist in the environment due to their stable chemical structures. In addition to these historical pollutants, a new generation of emerging contaminants has begun to proliferate, largely as a result of industrial activities, land-use changes, and the combustion of fossil fuels. These substances, including per- and poly-fluoroalkyl substances (PFASs) are increasingly being detected in ecosystems around the world. Once released into the environment, these pollutants can undergo biotransformation, bioaccumulation, and biomagnification within food webs, leading to severe biological effects across multiple species [1].

Various animal species, acting as sentinels, have provided early warnings of biological risks and environmental pollutants long before these threats become apparent to humans [2,3]. This concept of animals as environmental sentinels is deeply rooted in our understanding of ecological interdependence. Natterson-Horowitz and Bowers have poignantly highlighted this interconnectedness, likening all living beings to “canaries” in a global “coal mine”. This metaphor underscores the critical role that different species play in signaling the presence of environmental contaminants before they adversely affect human populations [4].

Sentinel organisms are species whose health, behavior, and physiological characteristics respond directly to changes in environmental conditions, making them essential indicators of ecosystem health [5–9]. These species are especially valuable for monitoring ecological shifts, as their responses often represent broader environmental stressor impacts on surrounding biota. Species that live in proximity to human settlements and have well-documented sensitivities to pollutants serve as particularly effective sentinels, revealing both the acute and chronic effects of exposure. Such effects often parallel those observed in human populations exposed to similar environmental conditions, thereby underscoring the relevance of sentinel data in environmental health studies [8–10]. By closely monitoring the health and behavior of these animals—such as pets, wildlife, and other companion species—researchers and public health officials can detect early signs of environmental risks. Early detection enables timely interventions that are essential for safeguarding human health and preventing extensive ecological damage

The concept of sentinel organisms is closely related to that of biomonitors, a broader category encompassing organisms used to gather quantitative data on environmental quality. Although both sentinels and biomonitors contribute valuable information for ecological assessments, sentinel organisms are uniquely advantageous due to their capacity to exhibit immediate, observable changes in health, serving effectively as early warning systems for environmental hazards [11–13]. This distinction is particularly valuable in environmental monitoring, where rapid detection and response to emerging threats are critical to mitigating adverse impacts.

Increasing awareness of environmental pollution as a significant human health risk has led to an expanded use of animals as sentinels, particularly in efforts to evaluate pollutant exposure levels and associated health outcomes. Raptors, for instance, are frequently studied for contamination levels as apex predators in various ecosystems. Their elevated susceptibility to the bioaccumulation of toxins renders them particularly sensitive indicators of environmental health [14–17]. This approach highlights the role of sentinel species in providing critical insights into the potential human health implications of environmental contaminants. The data collected from these and other sentinel species are crucial for evaluating the effectiveness of environmental regulations, guiding conservation efforts, and informing future research. Studying the health and behavior of sentinel species enables scientists to gain critical insights into the pathways through which pollutants circulate within ecosystems, accumulate in various organisms, and, ultimately, pose risks to human health [18–21]. This approach not only clarifies the mechanisms of pollutant transfer across trophic levels but also enhances our understanding of the broader ecological and public health implications associated with environmental contamination.

The aim of this review is to critically evaluate the role of the peregrine falcon (*Falco peregrinus*) as a sentinel species in monitoring environmental pollution. Specifically, this review seeks to explore the effectiveness of peregrine falcons in detecting and assessing the presence and impact of various pollutants, including heavy metals, brominated flame retardants, and organochlorine pesticides.

In selecting the groups of chemicals emphasized in the passage—organochlorine pesticides, heavy metals, and brominated flame retardants—specific criteria were meticulously considered to underscore their ecological significance concerning the peregrine falcon. Firstly, the inclusion of organochlorine pesticides is imperative due to their historically documented impact on peregrine falcon populations. These pesticides have been linked to detrimental effects such as eggshell thinning, which contributed to the decline of peregrine falcons in various regions [22]. Secondly, heavy metals, including lead, mercury, and cadmium, were selected because of their pervasive presence in the environment and their propensity for bioaccumulation. These metals pose substantial risks to peregrine falcons by compromising their immune systems and impairing their reproductive health, among other adverse effects [23,24]. The ability of these metals to accumulate in the food chain makes them particularly hazardous to apex predators like the peregrine falcon. Lastly, brominated flame retardants are highlighted, as they represent a newer class of persistent organic pollutants that continue to pose significant challenges. These compounds accumulate in wildlife, including peregrine falcons, and their persistent nature means they remain in the environment for extended periods, leading to chronic exposure and long-term health impacts [25,26]. The emerging concerns surrounding brominated flame retardants necessitate ongoing research and monitoring to mitigate their effects on both wildlife and ecosystems. By focusing on these specific groups of chemicals, the study effectively highlights the critical threats they pose to peregrine falcons, thereby emphasizing the need for continued environmental vigilance and conservation efforts.

Through an in-depth analysis of the existing research on pollutant exposure and the associated health effects in peregrine falcons, this review seeks to clarify the role of these apex predators as key indicators of ecological health and environmental quality. Due to their sensitivity to environmental changes, peregrine falcons provide invaluable insights that extend beyond conservation, offering critical understanding of the broader risks posed by environmental contaminants, including potential human health impacts. Their capacity to reflect the integrity of their ecosystems underscores the importance of monitoring such species, not only to safeguard biodiversity but also to inform public health strategies aimed at reducing pollutant exposure risks in human populations.

2. Materials and Methods

Data were gathered from the PubMed, Google Scholar, and MEDLINE databases. A range of search terms pertinent to the topic were employed, such as “Peregrine Falcon environmental pollutants”, “Peregrine Falcon contamination”,”environmental animal sentinels”, “endocrine disruptors in raptors”, “endocrine disruptors in birds of prey, “raptors as biomonitoring sentinels”, “birds of prey as biomonitoring sentinels”, organochlorine pesticides raptors”, “organochlorine pesticides Peregrine Falcon”, organochlorine pesticides birds of prey”, “DDT raptors”, “DDT birds of prey”, “DDT Peregrine Falcon”, “heavy metals in raptors”, “heavy metals in Peregrine Falcon”, “heavy metals in birds of prey”, “retardant flames in raptors”, “retardant flames in birds of prey“, and “retardant flames in Peregrine Falcon”. The arrangement of these terms dictated the use of operators like “AND” and “OR”. Only studies published in English were considered for the review.

3. The Use of Raptors as Sentinels

As environmental challenges intensify due to factors such as climate change, habitat destruction, and the introduction of new pollutants, the role of animals as sentinel species for detecting and monitoring environmental pollution will become increasingly vital. Sentinel species such as mussels, oysters, and fish are frequently analyzed for pollutants within their soft tissues, liver, and gills, providing valuable data on water quality and chemical exposure in aquatic ecosystems. Similarly, seabirds and marine mammals contribute feathers, blubber, and blood for contaminant analysis, while bees, frogs, and snails are regularly used to assess pollution levels in terrestrial and wetland environments. Even domestic pets, including dogs and cats, function as sentinels; samples from their liver, kidneys, bones, teeth, serum, and feces are examined to evaluate their exposure to various pollutants, reflecting the potential health risks that such contaminants pose to human populations as well [9,22].

This approach not only deepens our understanding of the impacts that pollutants have on wildlife but also serves as a critical tool for safeguarding human health. By offering early warnings of environmental hazards, sentinel organisms play a pivotal role in the ongoing effort to protect both ecological and human well-being in an increasingly contaminated world [21,23]. Numerous international initiatives focus on monitoring environmental contaminants and examining the role of sentinel animals. Notably, the 2019 ERBFacility workshop put forth a preliminary "long list" of species potentially suited for monitoring key pollutants across Europe. The workshop underscored that while active monitoring, such as through the collection of blood samples from nestlings, could establish a systematic and well-organized framework for tracking pollutants, achieving a sustainable program with broad geographical coverage presents significant challenges. These challenges stem from the need for ethical permits, the recruitment of trained volunteers or professional staff, and the considerable costs associated with such efforts. Although it is possible to collect other samples such as feathers or eggs lost in nests, this approach would not address the expected geographical inconsistencies in sampling and would offer limited toxicological value, especially with feathers. Espín et al. (2016) [19] thoroughly evaluated the benefits and limitations of various sample matrices for contaminant monitoring in raptors, concluding that the liver and blood are the most effective matrices for analyzing most contaminants. Liver samples can be sourced from dead raptors. Existing monitoring programs have proven the practicality of involving the public in reporting and collecting raptor carcasses [17,21,24,25], enabling collections over a broad geographical range. Consequently, the selection of species for biomonitoring was based on the premise that pollutant characterization would involve analyzing tissue samples from bird carcasses, particularly those that died due to various causes, such as traffic accidents, other traumas, and starvation [17,24,25].

4. Peregrine Falcons as Sentinels for Human and Environmental Health Hazards

4.1. Raptors as Indicator Species

The tracking of environmental pollutants in raptors has a well-established history, contributing significantly to our understanding of ecological health and safety [26,27]. Initially, above all, this monitoring has made it possible to assess the dangers posed by pollutants to certain species that are very important in conservation. However, it is now recognized that such tracking can provide valuable insights into broader ecological health and serve as an early warning system for potential human exposure and health risks [23]. Raptors, especially apex predators, are exceptionally well suited as indicator species for monitoring substances that bioaccumulate or biomagnify within food webs. Their effectiveness as indicators is due to several crucial factors: they forage across both terrestrial and aquatic food chains, occupy high trophic levels, and are backed by a substantial history of ecotoxicological research. Furthermore, raptors enable the collection of non-invasive samples, including feathers, carcasses from accidental deaths, abandoned eggs, and blood, which are valuable for detailed chemical analyses [19,21]. These attributes make raptors invaluable in assessing environmental contamination and the broader health of ecosystems.

4.2. Peregrine Falcons: Indicators of Human and Environmental Health Risks

Among raptors, the peregrine falcon stands out as one of the most widely distributed species globally, inhabiting every continent except Antarctica. In Europe, it predominantly occupies the western and southern regions, including Great Britain, France, and Spain, as well as northern areas of Scandinavia and Russia [28,29].

A growing number of peregrine falcons have adapted to urban environments, and this adaptability appears to play a significant role in their successful resurgence alongside human populations [30].

Peregrine falcons function as highly effective sentinel species for tracking environmental organic contaminants, serving a critical role in monitoring health hazards relevant to both human and ecological well-being. As avian predators positioned high in both aquatic and terrestrial food chains, peregrine falcons prey on a diverse range of species, including birds from aquatic environments (such as waders and ducks), terrestrial habitats (such as pigeons, starlings, and thrushes), and migratory populations (Smith et al., 2018) [27]. The dietary composition and ecological significance of peregrine falcons are summarized schematically in Figure 1. This high trophic position enables peregrine falcons to reflect pollutant levels across multiple ecosystems, underscoring their value in ecotoxicological research and environmental monitoring efforts. Their strong pair bonds, long life spans of 12–15 years, stable nesting sites with extended residency (7–9 years), and annual clutches of 3–5 eggs make them valuable indicators of regional variations in chemical pollution. The wide distribution of peregrine falcons across both rural and urban areas enhances their utility for large-scale spatial and temporal biomonitoring, allowing researchers to assess human impacts on terrestrial wildlife through the analysis of addled or unhatched eggs [31–33].

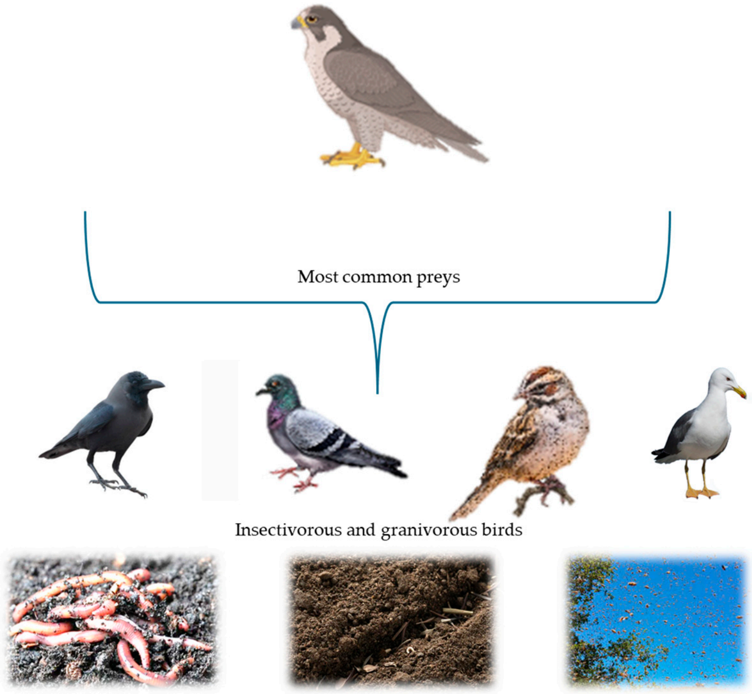

Figure 1. Dietary composition and ecological role of the peregrine falcon: a top predator in aquatic and terrestrial food chains.

4.3. Peregrine Falcons and Chemical Pollutants

Between 1950 and 1975, peregrine falcon populations experienced a dramatic decline in many countries, leading to local extinctions across vast regions. This decline was paralleled by similar decreases in other apex predators. The reduction in insect-eating bird populations, as highlighted by Carson (1962) [34], intensified the search for underlying causes. A significant milestone in conservation history, particularly concerning birds of prey, emerged following the widespread agricultural use of organochlorine pesticides, including DDT and cyclodiene compounds like aldrin and dieldrin. In the 1960s, Derek Ratcliffe [27] played a pivotal role in uncovering the link between these chemicals and the reproductive failure of birds of prey, including peregrine falcons. He provided both direct evidence, such as pesticide residues found in eggs, and indirect evidence, like the presence of thin-shelled eggs. What began as a hypothesis has since been established as scientific fact [35–37]. Alongside organochlorine pesticides, heavy metals and polychlorinated biphenyls (PCBs) also contributed to the decline of peregrine falcon populations. Monitoring these effects played a crucial role in the eventual ban of DDT in many countries, underlining the value of the species in signaling the wider environmental and health risks associated with certain chemicals [38].

4.4. Peregrine Falcons and Environmental Challenges

In addition to monitoring chemical pollutants, peregrine falcons are also valuable for assessing the impacts of emerging environmental challenges, such as climate change. Changes in prey availability, shifts in migration patterns, and the emergence of new diseases are potential hazards that could be detected through long-term studies of peregrine falcon populations [39]. By studying the concentrations of other harmful chemicals in peregrine falcons, scientists can gain insights into the levels of contamination in the environment and assess the potential risks to both wildlife and human health. This makes peregrine falcons not just important for conservation efforts but also key players in understanding and mitigating the impacts of human activities on the environment [40].

5. Resilience in the Skies: The Devastating Effects of Organochlorine Pesticides on Peregrine Falcons

Pesticides are chemicals designed to manage, kill, or deter pest plant and animal species, and their usage has a long history in agriculture and public health [41]. For centuries, these substances have been instrumental in protecting crops from damaging pests and controlling vector-borne diseases that affect humans [42,43]. The introduction of synthetic pesticides in the early 1940s revolutionized agriculture, but the unintended consequences of these chemicals have raised serious concerns regarding their impact on both the environment and human health [34,44].

Among the various pesticide classes, organochlorine pesticides have emerged as particularly harmful to ecosystems. These compounds are notorious for their persistence in the environment, leading to long-term ecological consequences [45]. They are linked to acute neurological damage and endocrine disorders in both wildlife and humans [46–48]. Specifically, DDT has been shown to adversely affect bird populations, notably causing reduced eggshell thickness and subsequent breeding failures [27]. Numerous studies have demonstrated a correlation between high concentrations of organochlorine pesticides and adverse effects on animal populations, including reproductive failures and increased mortality rates, particularly in species at higher trophic levels, such as birds of prey [45,49–52].

In the next paragraphs, special attention will be given to the effects of DDT and its metabolites (including DDD and DDE), as well as its degradation products, dieldrin, hexachlorobenzene (HCB), hexachlorocyclohexane (HCH), chlordane-related pesticides, and toxaphene in peregrine falcons. Although these compounds vary chemically, they have a similar history of production and use. Introduced in the mid-20th century, these pesticides were recognized as persistent organic pollutants. This recognition led to their ban in agricultural use across many Western countries during the 1970s and 1980s [53,54].

5.1. Dichlorodiphenyltrichloroethane

Dichlorodiphenyltrichloroethane (DDT) was first synthesized in 1873, but its significant use began during World War II to combat vector-borne diseases such as malaria and typhus [55,56]. After the war, DDT became widely available for agricultural and public health applications, effectively controlling pests and vectors [57]. Despite early warnings about its potential hazards in the 1940s, public awareness regarding DDT's dangers increased following the publication of Rachel Carson's influential book *Silent Spring* in 1962, which detailed its detrimental environmental effects [34,56].

The sub-lethal effects of DDE, a major DDT metabolite, have been linked to eggshell thinning and nesting failures, being first observed in robins in the late 1950s [34]. This thinning has subsequently driven declines in raptor populations globally [27,51,58–60].

The recovery of the peregrine falcon from the devastating effects of organochlorine pesticides, particularly DDT, is a remarkable story that unfolds across different time periods and geographical regions. This narrative underscores the complex relationship between the historical use of pesticides, their ecological consequences, and the evolving environmental dynamics. Initially celebrated for its effectiveness, DDT eventually became infamous for its long-lasting presence in the environment and its toxic impact on wildlife, particularly raptors like the peregrine falcon.

In the mid-20th century, DDT was widely used in agriculture and public health, significantly contributing to population declines of many bird species. Its metabolites, particularly p,p′-DDE, have been shown to cause serious reproductive issues in birds, including eggshell thinning, which was extensively documented in studies by Lundholm (1997) [61] and Peakall and Kiff [62]. These vulnerabilities emphasize the urgent need for ongoing research and environmental monitoring. Even decades after DDT was banned in many countries, its legacy endures, as the chemical and its byproducts continue to contaminate ecosystems, threatening wildlife in even the most remote areas, such as the Arctic [63].

Research tracking pesticide concentrations over time reveals significant trends, painting a complex picture of recovery and ongoing challenges. For instance, an analysis of peregrine falcon eggs collected between 1985 and 2003 revealed concerning levels of p,p′-DDE comparable to populations in Alaska and Norway but significantly lower than those found in the Canadian Arctic and parts of the United States [64–66]. This disparity suggests that while regulatory measures have effectively reduced pesticide exposure in some regions, others still grapple with the historical ramifications of pesticide use.

As evidence mounted, the USA, the UK, and several European nations banned DDT in the 1970s and 1980s due to its harmful effects on health and ecosystems [67,68].

5.2. Dieldrin

Dieldrin, developed in the late 1940s as a DDT alternative, peaked in use during the 1960s and 70s but was banned in the USA by 1987 due to its severe toxicity [69,70]. Most of Europe followed suit by 1990. However, DDT and dieldrin continue to be produced and used in parts of the developing world, highlighting a persistent issue in global pesticide management [71–74].

Dieldrin has been implicated in the decline of global raptor populations. Unlike DDT, dieldrin does not induce eggshell thinning [45,75]. Nevertheless, its toxicity is considerable, with lethal doses (LD50s) reported to range from 27 mg/kg to 381 mg/kg across various avian species [76,77]. Dieldrin adversely affects neurotransmitter systems, specifically reducing the levels of serotonin and dopamine, which are critical for cognitive and motor skill development [78]. Elevated exposure levels to dieldrin can result in increased mortality due to accidents, disease, and starvation [51,78].

More than a decade after their bans in the Global North, the Stockholm Convention on Persistent Organic Pollutants was adopted by over 90 countries, aiming to protect human health and the environment from persistent chemicals, including DDT and dieldrin [79]. Nonetheless, in 2006, the World Health Organization endorsed the reintroduction of DDT for vector control in certain tropical countries, leading to its legal production and use in some developing nations [80,81].

Although significant research has been conducted on organochlorine pesticides, there is a lack of comprehensive reviews that bring together monitoring data from across the global environment. Most existing studies tend to focus on particular regions or species. For example, Muir et al. (1999) [82] conducted a review of organochlorine pesticide levels in marine species of the Canadian Arctic. Their findings highlighted that the data on DDT in particular are often specific to certain regions and species. Similarly, Loganathan and Kannan (1994) [83] noted a significant gap in monitoring organochlorine pesticides in the Global South compared to the North. Kutz et al. (1991) [84] and Smith (1999) [85] demonstrated that less than 10% of samples analyzed for DDT levels were from the Global South, despite these areas being recognized as contamination hotspots.

While DDT is primarily recognized for causing eggshell thinning and associated reproductive failures, the abrupt decline in raptor populations indicates that reproductive impairment alone cannot account for the observed decreases [45,51]. Consequently, researchers suggest that these declines may be attributable to a combination of factors, including the reproductive effects of DDT and its metabolites, such as DDE, alongside increased mortality rates linked to dieldrin exposure [86]. This multifactorial perspective underscores the necessity for comprehensive strategies aimed at addressing the decline of raptor populations as a consequence of both pesticides.

The biomagnification of organochlorine pesticides through food webs presents serious risks to species higher up the trophic levels. In particular, raptors have exhibited negative demographic effects due to DDT and dieldrin exposure [87–89].

5.3. Hexachlorobenzene

Introduced in 1945 as a fungicide, hexachlorobenzene has been utilized in producing pyrotechnics and rubber chemicals. HCH, consisting of several isomers with only γ-HCH (lindane) possessing insecticidal properties, was initially used as technical HCH, which contained a mixture of five isomers [53]. Although technical HCH was phased out in many Western countries during the 1970s, significant quantities were released into the environment between 1948 and 1997 [90].

5.4. Chlordane

Chlordane was widely used in the USA and Japan as an insecticide and termiticide, with an estimated total global production of about 70,000 tons until the mid-1980s [91]. Toxaphene, which was introduced in the late 1940s, was produced in large quantities (approximately 1.3 million tons) and primarily used in the USA, Central America, and the former Soviet Union [92]. All these organochlorine compounds, except HCH, were included in the “dirty dozen” list of the Stockholm Convention, which mandated global bans in 2004. However, DDT remains listed under Annex B, allowing its restricted use for vector control [80].

DDT and organochlorine pesticides in peregrine falcons across various geographical regions and in various matrices are summarized in Table 1.

Table 1. Chemical pollutants detected in peregrine falcons (*Falco peregrinus*) across various geographical regions and in various matrices (DDT: dichlorodiphenyltrichloroethane; PCBs: polychlorinated biphenyls; PBDE: polybrominated diphenyl ether; (OH): hydroxylated PBDE; PCB-related TEQ: PCB-related toxic equivalent; TCDD-TEQ: 2,3,7,8-tetrachlorodibenzo-p-dioxin-related toxic equivalent).

Compounds	Sample Types and Results	Location	Reference
Sum of DDT; sum of PCBs	Eggs, severe shell thinning and very depressed species	Norway: since 1990	[93]
p,p′-DDE PCBs (1.8–2.4 ppm in serum) (dieldrin: max 0.27 mg/kg–0.30 mg/kg) Local weather patterns	Blood serum from both sexes Decline in occupancy and reproduction	Nunavut, Canada (19822009)	[94]
PCBs, PBDE, and OH-PCB	Blood plasma (nestlings)	Great Lakes, Canada (2044–2005)	[95]
PCB-related TEQ compared to TCDD-TEQ	Eggs	Mid-Atlantic States (1993–1999)	[96]
DDT and dieldrin	Thinner eggshells: 1970–80–90 Lower breeding success due to reduced no. of colonial seabirds	Norway (1976–2017)	[97]

Investigations into additional organochlorine compounds, such as HCB, HCH, and chlordane, yielded mixed results. Between 1986 and 2003, the concentrations of HCB and chlordane showed significant declines, while HCH levels experienced only a marginal decrease. In contrast, the toxaphene concentrations generally increased, highlighting the regional variability in the effectiveness of environmental management strategies [98]. Overall, the decline in ΣDDT levels can largely be attributed to the ban implemented in the 1970s, which marked a pivotal milestone in the efforts to mitigate the harmful impacts of these chemicals on wildlife [99,100].

6. Recovery Trajectory of Peregrine Falcons in Europe

The recovery trajectory of peregrine falcons in Norway offers a compelling case study. The broader Norwegian population was estimated to be between 700 and 1000 pairs in 2013, numbers reminiscent of those observed prior to the 1940s [97]. This rebound indicates that as populations recover, they may reach a stage where density-dependent factors could start to regulate growth. The distribution of peregrine falcons in Norway has shifted from coastal regions to fjords and inland breeding sites, a change that is likely associated with alterations in food availability and broader environmental dynamics. Reduced exposure to harmful pollutants suggests that ecological factors, rather than pollution, now drive population changes. This shift aligns with broader trends impacting seabird species, a primary food source for coastal peregrines. Declines in seabird populations due to climate change, overfishing, aquaculture expansion, and natural ecosystem shifts in the North Atlantic have altered the trophic dynamics that directly affect peregrine falcons, the apex predators of their environment.

In Scotland, the recovery narrative unfolds distinctly over four decades, being characterized by three distinct phases: the pesticide period, the recovery phase, and the stable period [101]. The pesticide period, lasting until 1973, witnessed alarmingly low hatching and fledging success rates, particularly in southeastern Scotland, where intensive agricultural practices exacerbated pesticide exposure. Following the reduction of pesticide use, hatching success dramatically increased in southeastern peregrines, which became 9.7 times more likely to succeed during the stable period compared to the pesticide era. Similarly, fledging success increased 13.1 times, highlighting the direct correlation between reduced pesticide use and improved reproductive outcomes. Although southwestern Scotland, with its pastoral and forested landscapes, also experienced improvements, the effects were less pronounced. The more intensive agricultural practices in the southeast likely accounted for the greater adverse effects observed in that region.

Interestingly, by the 1990s, while reproductive measures in southeastern Scotland rebounded to levels comparable to those in the southwest, southwestern peregrines began to experience declines in reproductive success. This decline was attributed to changes in pigeon racing routes, which led to a reduction in the availability of domestic and feral pigeons, the key prey species for peregrines in this region. Pigeons constituted over 50% of the diet by biomass for these falcons, underscoring the critical importance of prey availability for reproductive success.

7. Tissue Exposition

In a recent study by Padayachee et al. (2023) [102], the presence of DDT and dieldrin was assessed across various tissues from both live and deceased raptors. The variability in contaminant loads among individuals presents challenges in making cross-site and cross-species comparisons. Different tissues indicate different exposure histories; for instance, adipose tissue reflects chronic exposure, while liver samples indicate more recent exposure [19]. Moreover, factors like starvation, intoxication, and molting can lead to high variation in contaminant loads among individuals, complicating data interpretation.

The challenges of comparing contaminant levels across studies underscore the need for standardized monitoring practices. This need extends beyond organochlorine pesticides like DDT and dieldrin; it applies to all contaminant monitoring efforts aimed at facilitating cross-comparisons over time and space.

For contaminant monitoring in peregrine falcons, various sample matrices have been evaluated to determine their effectiveness in detecting pollutants. Liver and blood are among the most widely used matrices due to their ability to provide accurate and comprehensive data on contaminant levels. Espín et al. (2016) [19] emphasized that liver samples are particularly effective for analyzing a wide range of contaminants, as they accumulate many pollutants over time, making them a reliable indicator of long-term exposure. Blood samples are also valuable, especially for assessing recent exposure to contaminants, offering insights into the immediate toxicological status of the bird. Additionally, feathers have been used as non-invasive matrices, although they are less reliable due to their limited capacity to reflect the full spectrum of contaminants and their susceptibility to external contamination [21]. Eggshells and failed eggs serve as alternative matrices, particularly valuable for assessing contamination levels during the breeding season [103]. However, they have limitations, particularly in terms of geographical sampling consistency [25].

The geographical bias in studies on persistent organic pollutants, such as DDT and dieldrin, is a significant concern, with the majority of research concentrated in Europe and North America [104–107]. This bias hampers our understanding of contaminant dynamics in tropical regions, which harbor a significant portion of the world's biodiversity. The continued use of DDT and dieldrin in the Global South poses ongoing risks to biodiversity in those regions [108,109]. While DDT remains crucial for vector control in these areas, the findings of Padayachee et al. (2023) [102] emphasize the importance of monitoring to inform effective contaminant management decisions. This need for ongoing research and monitoring echoes across studies involving various species, including birds, bats, and sea turtles, highlighting the critical need for a more unified approach to environmental health and contaminant monitoring worldwide. Table 2 summarizes the documented effects of environmental pollutants on the health of the peregrine falcon.

Table 2. Chemical pollutant toxic effects detected in peregrine falcons.

Compounds	Chemical Names	Toxic Effects	References
Organochlorines	DDT, DDD, dicofol, Eldrin, dieldrin, chlorobenziate, lindane, BHC, methoxychloro aldrin, chlordane, heptachlor, endosulfan, isodrin, isobenzan, toxaphene, and chloro propylate	Moderately hazardous, high persistence, and a half-life of 2–15 years Stimulation of the central nervous system by cyclodienes, such as the GABA antagonists endosulfan and lindane, inhibits calcium ion influx and Ca- and Mg-ATPase, causing the release of neurotransmitters	[46,110,111]
DDT	Dichlorodiphenyltrichloroethane	Egg shell thinning	[110]
1,1-dichlo-ro-2,2-bis[4-chlorophenyl]ethylene affected eggshell thickness [29] and reproduction, while other organochlorines and mercury were linked to decreased survival [30]	Egg lipid extraction	Sweden	[112]
DDT and dieldrin	Thinner eggshells: 1970-80-90 Lower breeding success due to reduced no. of colonial seabirds	Norway (1976–2017)	[97]

8. Heavy Metal Exposure in Peregrine Falcons: Ecological Implications and Health Risks in Birds of Prey

Birds of prey, or raptors, are integral components of many ecosystems, functioning as both scavengers and predators. With their long life cycles, these birds play a crucial role in maintaining ecological balance by removing dead or sick animals from their habitats and preying on various species, thus regulating the populations of other wildlife [113]. Their diets are influenced by a multitude of factors, including geographical location, seasonal availability of prey, age, and sex, which, in turn, provide insights into the concentrations of heavy metals present in their environments [113]. One species that has garnered significant attention in the context of heavy metal contamination is the peregrine falcon. As a top predator, the peregrine falcon is particularly vulnerable to the bioaccumulation of heavy metals due to its position at the apex of the food chain [113]. The phenomenon of biomagnification leads to elevated levels of metals in these birds, as they consume prey that has accumulated toxins from lower trophic levels [114]. Once these metals enter the peregrine falcon's system, they can accumulate in critical internal organs, such as the kidneys and liver, potentially compromising the bird's health and reproductive success [102]. Heavy metals can be excreted from the body through various mechanisms. One method of excretion involves sequestration in feathers, where contaminants are concentrated and eventually shed [115]. Other pathways include elimination via the digestive system into feces [116,117]. Female peregrine falcons have the additional capability of excreting metals through their eggs and eggshells, with concentrations in these reproductive materials reflecting the female's metal levels during egg formation [115,118,119]. Blood metal levels in these birds provide an indication of recent dietary intake and mobilization from internal tissues, underscoring the dynamic relationship between metal exposure and physiological health [120]. In juvenile peregrine falcons, metal exposure predominantly arises from local dietary sources [121]. Notably, metals such as copper, zinc, and cadmium accumulate in the liver and kidneys, binding to metallothionein proteins, which play a role in detoxification [122,123]. Additionally, platinum group elements (PGE)—specifically platinum (Pt), palladium (Pd), and rhodium (Rh)—are primarily found in the feathers of raptors. Higher concentrations of palladium in these birds suggest greater environmental mobility and the potential for accumulation [124–126].

Sources of heavy metals in the environment encompass natural geological processes, industrial activities, agriculture, pharmaceuticals, household waste, and atmospheric deposition [127]. Environmental contamination is particularly severe in areas with concentrated activities, such as mining, smelting operations, and other metal-based industrial activities [127,128]. Industrial contributions to metal pollution include processes such as metal refining, coal combustion in power plants, petroleum burning, nuclear power generation, and high-voltage power lines, as well as operations in plastics, textiles, microelectronics, wood preservation, and paper production [129–131]. Certain metals like cobalt (Co), copper (Cu), chromium (Cr), iron (Fe), magnesium (Mg), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn) are essential nutrients necessary for various biochemical and physiological processes. A deficiency in these micronutrients can lead to various health issues [131]. These essential heavy metals play critical roles in both plants and animals, as they are integral components of several key enzymes and are involved in important oxidation–reduction reactions [13]. However, for some metals, such as chromium and copper, there is a narrow margin between beneficial and toxic levels. Other metals, including aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), bismuth (Bi), cadmium (Cd), gallium (Ga), germanium (Ge), gold (Au), indium (In), lead (Pb), lithium (Li), mercury (Hg), nickel (Ni), platinum (Pt), silver (Ag), strontium (Sr), tellurium (Te), thallium (Tl), tin (Sn), titanium (Ti), vanadium (V), and uranium (U), do not have known biological functions and are classified as non-essential metals [131].

Heavy metals and metalloids exert various detrimental effects at the molecular level in living organisms: Fe^{2+} (iron ion) and Cu^{+} (copper ion) can undergo auto-oxidation, leading to the formation of reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH). These ROS are highly reactive and can induce oxidative stress within cells. For instance, the accumulation of H_2O_2 has been linked to increased programmed cell death, or apoptosis. Meanwhile, hydroxyl radicals are known to initiate free radical chain reactions that cause irreversible damage to essential cellular molecules, including carbohydrates, DNA, proteins, and lipids [132]. These molecular disruptions underscore the profound impact of heavy metal exposure on cellular integrity and function.

In peregrine falcons, lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) are identified as priority pollutants due to their significant distribution and harmful effects. The heavy metals in peregrine falcons across various geographical regions and in various matrices are summarized in Table 3.

Lead is one of the most toxic heavy metals, posing a significant threat to both human and wildlife health due to its widespread distribution and persistence in the environment. Birds, particularly raptors, are among the most affected organisms, with extensive documentation of their exposure to lead and the consequent effects of lead contamination over several decades [133]. Raptors, such as the peregrine falcon, serve as vital indicators of environmental pollution, reflecting broader ecological risks, including those to human health [134]. Lead exposure in raptors primarily arises from anthropogenic sources, including lead-based gasoline, industrial activities, and, notably, lead ammunition used in hunting [135,136]. When hunters use lead-based bullets or shot, lead fragments often remain in the carcasses of the hunted animals. These carcasses are subsequently scavenged by raptors, including peregrine falcons. The ingestion of lead fragments results in the rapid dissolution of lead in the acidic environment of the raptor's stomach, allowing it to enter the bloodstream and be distributed throughout the body, affecting multiple organs such as the liver, kidneys, bones, and even growing feathers [134]. The retention of lead in a raptor's body varies by tissue type. For instance, bones can retain elevated lead levels for years, providing a measure of lifetime exposure, while soft tissues like the liver and kidneys, as well as blood, typically exhibit a shorter half-life for lead, ranging from weeks to months [136]. This variability in lead retention allows researchers to assess both recent and chronic exposure levels in peregrine falcons.

The sub-clinical effects of lead exposure can significantly impact their vascular, nervous, renal, immune, and reproductive systems. Furthermore, lead poisoning can lead to altered behavior, impaired survival, and even sudden death in otherwise healthy birds [136,137]. Given the documented risks posed by lead, numerous countries have moved to regulate or ban lead in ammunition. In Europe, the Bern Convention initiated the phase-out of lead shot in 1991, leading to further regulations across the European Union (EU) and associated countries [138,139]. However, the lack of harmonized legislation across the EU has resulted in the inconsistent implementation and enforcement of lead restrictions. This inconsistency has prompted the European Chemicals Agency (ECHA) to call for EU-wide action to mitigate the environmental risks posed by lead [140]. Recent studies underscore the conservation implications of lead contamination in raptors, identifying it as a significant conservation problem [134,141]. Among the raptor species frequently reported with lead concentrations exceeding sub-clinical and lethal thresholds are the bearded vulture, griffon vulture, red kite, common buzzard, and, notably, the peregrine falcon. The ingestion of lead shot or fragments remains the primary source of exposure for these birds, although urban and industrial pollution also contributes to lead contamination. The sub-clinical effects of lead in peregrine falcons include oxidative stress, DNA damage, and disrupted enzymatic activity, which can compromise their health and reproductive success [134]. Acute lead toxicity is a significant cause of mortality, with lethal concentrations reported in various raptor species, including peregrine falcons, across numerous studies. The concentration of lead in the bones, liver, and blood of peregrine falcons is particularly concerning due to its neurotoxic effects, which can impair neurological function, reduce reproductive success, and increase mortality rates [134,135]. The persistence of lead in the environment might pose a critical threat to peregrine falcons and other raptors, necessitating more comprehensive regulatory measures and ongoing research to mitigate its impacts on wildlife and human health.

Mercury contamination is a significant environmental issue impacting ecosystems worldwide, primarily due to anthropogenic activities that release this toxic metal into the environment. Once introduced, mercury undergoes methylation, transforming into methylmercury (MeHg), which is the most toxic and biologically available form. This substance biomagnifies through food webs, posing substantial risks to wildlife, particularly apex predators like the peregrine falcon, whose health and reproductive success are critical indicators of environmental integrity [142–145]. As top predators in terrestrial ecosystems, peregrine falcons primarily prey on other birds, making them particularly vulnerable to MeHg exposure. Many of their prey species accumulate MeHg from aquatic environments, increasing the risk of toxicity for the falcons [146,147]. Research shows that even low mercury levels can adversely affect immune function, behavior, and reproductive success in raptors, including peregrine falcons [145,148]. The primary pathway for mercury exposure in these falcons is through their diet, wherein they consume prey that have ingested contaminated food, thus introducing MeHg into their systems [145,149]. Monitoring feather mercury concentrations in raptors serves as an effective method for assessing exposure levels. Feathers provide a historical record of dietary intake, reflecting MeHg concentrations in the bloodstream during growth [145]. Feather sampling is less invasive than blood or egg sampling, allowing for broader studies across extensive geographic regions [145,150]. Studies have shown that peregrine falcons can accumulate significant mercury levels in their feathers, with variations based on their feeding habits, habitat, and geographical location [145,151]. Several studies indicate that adult peregrine falcons generally exhibit higher mercury concentrations in their feathers compared to juveniles. This difference may be attributed to the cumulative nature of MeHg exposure over time, as adults typically feed at higher trophic levels [143,144]. Variations in foraging strategies and prey availability can also lead to differences in mercury exposure among populations. For example, those that primarily consume insectivorous songbirds may experience higher mercury levels due to the dietary habits of their prey, which often includes invertebrates from aquatic ecosystems [146]. Temporal trends in mercury concentrations provide a better understanding of changes in environmental conditions. Some studies report no significant trends in the mercury levels in peregrine falcons over extended periods, suggesting stable exposure in certain regions [151] However, localized studies indicate fluctuating concentrations, underscoring the need for continuous monitoring to evaluate the effects of environmental policies and land-use changes.

Cd exposure in birds of prey varies depending on the source and duration of exposure. Blood samples typically indicate recent exposure, while feathers reflect prolonged exposure.

Factors such as age, the sampling time, and location are critical for accurately interpreting Cd levels. Juvenile raptors generally exhibit lower Cd concentrations, whereas adults can accumulate levels up to ten times higher [152]. Cd exposure, often coupled with lead, disrupts the endocrine system, impairing development, growth, feather molting, and migration [125,152–154]. Additionally, Cd can cause respiratory diseases, inhibit egg production, and reduce eggshell thickness. Cd is primarily introduced into the environment through fertilizers, accumulating in soil and water bodies. It is also found in cereals, vegetables, and tubers [125,152–154], which are consumed by rodents, common prey for raptors. This allows Cd to enter the food chain, leading to ingestion by birds of prey. This pathway underscores the significant risks posed by agricultural practices and environmental contamination, particularly to raptors at the top of the food chain. Prolonged Cd exposure in peregrine falcons, for instance, leads to accumulation in their kidneys and liver, resulting in severe health issues, including kidney damage [125,152–154]. Cd is a critical environmental pollutant, even at low levels, causing oxidative stress and irreversible cellular damage due to its high absorption and bioaccumulation [125,152–154].

Recent studies focus on the stomach contents of raptors, revealing traces of arsenic. One significant source is arsenopyrite (FeAsS) in agricultural pesticides and herbicides [139,152]. Raptors often feed on small- and medium-sized mammals on farmland, which ingest arsenic through their diet. This pathway highlights the importance of understanding the impact of agricultural practices on wildlife and the potential risks posed by bioaccumulation in food chains. Arsenic, which enters the environment from both natural sources and human activities such as mining and pesticide use, can also pose a risk to peregrine falcons. While the effects of arsenic on peregrine falcons are less well documented than those of lead or mercury, it is known that arsenic can cause organ damage and weaken the immune system of birds [139,152].

Over recent decades, the environmental accumulation of PGEs has increased due to their widespread use in automobile catalysts. These metals are released into the environment primarily through surface abrasion of catalytic converters during vehicle operation, with emissions of metallic PGE particles occurring in the micrometer and submicrometer range [124,125,155,156]. These particles can settle in various ecosystems, leading to significant concentrations of PGEs in the soil, water, and, ultimately, the food chain [124,125,157]. Top predators, such as the peregrine falcon, are particularly vulnerable to the bioaccumulation of these metals. As apex predators, peregrine falcons are at the end of the food chain and can accumulate high levels of PGEs through the consumption of contaminated prey. This bioaccumulation is concerning, as PGEs, which were once considered relatively inert, are now known to undergo environmental transformations into more reactive and bioavailable species [124,157]. Studies on peregrine falcons have shown that PGE concentrations are particularly high in the blood compared to other tissues, such as the liver and kidneys, with Pt levels being notably elevated [124]. This suggests that blood acts as a primary transport medium for PGEs, redistributing them throughout the body and potentially leading to accumulation in vital organs. The study by Jensen et al. (2002) [124] found that PGE concentrations in peregrine falcon eggs from 1992 to 2000 did not show significant temporal trends when compared to those from 1974 to 1977, indicating a consistent exposure over time. Pd, among the PGEs, has been identified as the most mobile element, with a higher propensity for bioaccumulation in tissues such as the liver, kidneys, and eggs. Pd also shows higher mobility into feathers compared to Pt and Rh, indicating its potential for greater bioavailability and environmental persistence [124,125,156,158]. This mobility gradient, where Pd > Rh > Pt, poses a significant concern for peregrine falcons, as it suggests that Pd could lead to higher toxicity levels due to its greater environmental mobility and ease of incorporation into biological tissues. Interestingly, while a spatial trend was observed for Pt levels in feces, with higher concentrations in peregrine falcons from northern Sweden, there was no significant spatial difference in PGE levels in the blood, egg, and feces between peregrine falcons from northern and southern Sweden [124]. This suggests that PGE exposure is consistent across different regions, regardless of whether the falcons are at the top of an aquatic or terrestrial food chain. The mechanisms by which PGEs are excreted from the body include sequestration in feathers, excretion through the digestive tract, and, in females, deposition in eggs and eggshells [115,119]. However, the study found no evidence for bioaccumulation through metallothionein pathways, proteins that are typically involved in metal sequestration in biological tissues [124,125]. This suggests that PGEs may be stored in the body in different forms or excreted via alternative pathways.

Table 3. Heavy metals detected in peregrine falcons (*Falco peregrinus*) across various geographical regions and in various matrices (Cu: copper; Zn: zinc; PGEs: platinum elements; Pt: platinum; Pd: palladium; Rh: rhodium; THg: total mercury).

Compounds	Sample Types and Effects	Location	Reference
Pb (2.26 µg/g), Cu (15.42 µg/g), and Zn (42.05 µg/g) Pb (1.08 µg/g), Cu (11.33 µg/g), and Zn (22.04 µg/g)	Feces and feathers, toxic effects	Lublin, Pulawy	[152]
Mg (47,01), Fe (11,14), and Zn (5,83)	Eggs: all below the critical ranges	Mid-Atlantic States	[96]
Pb (0.74 ppm; 1.40 ppm; 0.14)	Liver, kidneys, and blood: not significant concentrations	Baltimore	[159]
Hg	Feathers (adults and nestlings)	Sweden (1971–1978)	[160]
Pb, Cu+, Zn+, Pt, and Cd Pb+, Cd, Cu, and Zn+ Pb++, Cd, Cu, and Zn Pb++, Cu, Zn+, and Cd Pb+, Cu++, Cd++, and Zn++	Feathers (adults) (1998–2000) Egg contents (1992–2000) Feces, adults and juveniles (1997 and 2000) Blood (juveniles) (2000–2001) Liver and kidneys (adults) (1985–1995)	Sweden (1998–2000)	[126]
Hg	Feathers (juveniles and adults)	West Greenland (1851–2003)	[161]
Hg	Eggs: no abnormalities in reproduction	France (1974–1978–1979)	[162]
Pt++, Rh++, Pd, and Rh	Blood, eggs, feathers, feces, liver, and kidneys	Sweden (1974–1977 vs. 1992–2000)	[125]
Pb	Liver	UK (1980s–1990s)	[163]
THg++	Breast feathers	North America (2002–2014)	[145]
Pb	Liver+ and bone++	Canada (1995–2001)	[164]
Pt+ (1917–1999), Pd++, Rh+ (from 1986)	Feathers	Sweden (1917–1999)	[124]
Hg+, Se++	Feathers and liver Low reproductive rates	Texas (USA) (1994–1998)	[165]
Hg±	Eggs, eggshell fragments Declines in breeding and productivity	Norway (1970–2016)	[97]

+++ = high levels; ++ = moderate levels; + = low/mild levels; ± = not significant.

9. The Dual-Edged Sword of Brominated Flame Retardants: Balancing Fire Safety and Environmental Health Risks in Peregrine Falcons

Flame retardants (FRs) encompass a wide and diverse array of chemicals designed to inhibit or delay the ignition and spread of fire. These substances are commonly incorporated into various consumer products, including plastics, textiles—such as those used in furniture—and surface finishes in electronics [166–170]. The primary goal of FRs is to enhance fire safety by reducing the flammability of materials. However, their environmental impact and potential toxicity, particularly to wildlife, have emerged as significant concerns in recent years. FRs can be categorized based on their chemical composition into several types, including brominated flame retardants (BFRs), chlorinated flame retardants (CFRs), and organophosphate flame retardants (OPEs). Among these, BFRs have been the most widely used and studied due to their effectiveness in various applications across different industries. However, the environmental persistence and bioaccumulation of many BFRs have raised serious concerns about their impact on health and ecosystems.

BFRs can be further classified into different groups according to their chemical structure and usage. The most studied and widely used BFRs include polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), and brominated biphenyls (BBs). PBDEs, for instance, were commonly used in three commercial mixtures—PentaBDE, OctaBDE, and DecaBDE—with each designed for specific applications depending on the types of polymer materials they were added to. The global production of these PBDEs has been significant, with DecaBDE accounting for the highest production volume, estimated at around 1.25 million tons since the 1970s [167,171].

HBCD is one of the most prominent BFRs primarily utilized as a FR in polystyrene foams used for building insulation. Unlike PBDEs, which were predominantly used in North America, HBCD saw higher usage in Europe [169]. The commercial HBCD mixture consists of several isomers, with γ-HBCD being the most dominant. One of the most alarming features of BFRs is their environmental persistence. Compounds like PBDEs and HBCD are highly resistant to degradation, allowing them to linger in the environment long after their initial application. This persistence is compounded by the tendency of these chemicals to bioaccumulate, particularly in top predators within both aquatic and terrestrial food webs. For example, PBDEs have been detected in high concentrations in birds of prey, such as peregrine falcons, indicating significant biomagnification [172–174].

The toxicity of BFRs is another critical issue. PBDEs, for instance, share many toxicological properties with other halogenated compounds such as DDT. These compounds are known to disrupt endocrine function, impair reproductive health, and cause neurodevelopmental effects in wildlife and humans [175]. The structural similarity between PBDEs and thyroid hormones suggests that these compounds could interfere with thyroid hormone homeostasis, potentially leading to developmental and metabolic disorders [175].

The widespread use of BFRs and the associated environmental and health risks have led to increased regulatory scrutiny. Many BFRs have been phased out or restricted under international agreements, most notably the Stockholm Convention on POPs. This treaty aims to eliminate or restrict the production and use of chemicals that are persistent in the environment and pose significant health risks. Several BFRs, including PBDEs, HBCD, and hexabromobiphenyl (HBB), have been listed under the Stockholm Convention due to their persistence, bioaccumulation, and toxicity. Specifically, PBDEs, particularly PentaBDE and OctaBDE, were included in the Convention in 2009, leading to a global ban on their production and use. Furthermore, DecaBDE was added to the Convention in 2017 [176]. The inclusion of these chemicals in international agreements has led to a significant reduction in their production and use globally.

Despite these regulatory efforts, the environmental residues of BFRs remain a pressing concern due to their persistence and the ongoing release from products still in use. HBCD was included in the Stockholm Convention in 2013, although specific exemptions allow for its continued use in certain applications, such as building insulation, provided the materials are labeled appropriately [177]. This regulation reflects the challenge of balancing the need for fire safety with the imperative to protect environmental and human health.

The phaseout of legacy BFRs like PBDEs and HBCD has prompted the introduction of alternative flame retardants, including novel brominated flame retardants (NFRs). These alternatives, such as bis(2-ethylhexyl)tetrabromophthalate (BEH-TEBP), 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB), and decabromodiphenyl ethane (DBDPE), have been detected in increasing concentrations in various environmental settings [178]. Although NFRs were developed to replace phased-out BFRs, there is growing evidence that these newer compounds may also pose environmental and health risks. For example, BEH-

TEBP and EH-TBB, which are components of commercial flame retardant mixtures such as Firemaster 550®, have been found to bioaccumulate in wildlife [179]. Additionally, these compounds are structurally similar to known endocrine disruptors, raising further concerns about their potential toxicological effects [180].

Research on BFRs, particularly in peregrine falcons, is still relatively limited, but it offers vital insights into the accumulation of pollutants in avian species, especially top predators. BFRs, including polybrominated diphenyl ethers (PBDEs) and HBCDD, are persistent organic pollutants that can bioaccumulate in the environment and are known to exert detrimental effects on wildlife. BFRs in peregrine falcons across various geographical regions and in various matrices are summarized in Table 4.

Table 4. Brominated flame retardants detected in peregrine falcons (*Falco peregrinus*) across various geographical regions and in various matrices (PBDEs: polybrominated diphenyl ethers; PCBs: polychlorinated biphenyls; 4,4′-DDE: 1,1-dichloro-2,2-bis(p-chlorophenyl)ethylene; DBDE: decabromodiphenyl ether; HBCD: hexabromocyclododecane; BDE-209: decabromodiphenyl ether; HBCDD: hexabromocyclododecane; BB-153: 2,2′,4,4′,5,5′-hexabromobiphenyl).

Compounds	Sample Types and Effects	Location	Reference
PBDEs+++, DPTEs++, HBCD+, HBB+, TBP±, TBA±, PBEB±, and PBT±	Egg yolks (lipid extraction)	Germany (2014)	[181]
PBDEs>HBCD>BB-153>BTBPE>OBIND>HBB>BEHTBP	Whole eggs	Canada and Spain (2003–2009)	[182]
BDEs and HBCD>1974–2000 BDE-209 and HBCD>>	Egg contents	Sweden (1974–2007)	[174]
PBDEs	Eggs (lipid extraction):	USA (1986–2007)	[183]
PCBs and 4,4′-DDE>PBDEs	Egg contents	USA (1993–2002)	[184]
HBCD>DBDE	Egg contents	UK (1970s-2002)	[185]
HBCDD, BDE-209, and -153 BDE-209 BDE-209, -153, and -183	Egg homogenates Feces Plasma	Sweden (1998–1999, 2006)	[33]
BDE-209++, BB-153±, and DPTE±	Eggs	Greenland (1986–2014)	[186]

+++ = high levels; ++ = moderate levels; + = low/mild levels; ± = not significant.

While studies on American kestrels (*Falco sparverius*) have shown significant negative impacts of BFR exposure at environmentally relevant levels, the potential risks to peregrine falcons are of great concern. Research has demonstrated that PBDEs can impair immune function, disrupt hormonal balance, and affect behavior, leading to serious reproductive issues [187]. Similar adverse outcomes have been documented in kestrels exposed to HBCDD, which further raises alarms regarding the implications for peregrine falcons given the ecological similarities between these two raptor species [188].

Studies have detected significant concentrations of BFRs in peregrine falcon eggs, particularly in Europe and North America, indicating that these persistent chemicals are accumulating in their bodies [172–174]. The concern over PBDEs and other BFRs lies in their potential endocrine-disrupting effects, which can impair reproductive health and development, ultimately threatening the populations of these raptors [95]. Temporal analyses of BFR concentrations in peregrine falcon eggs reveal valuable insights into the historical usage patterns and environmental impact of these chemicals, particularly in Europe. A study by Johansson et al. (2011) [174] provides a significant reference point for understanding how the levels of BFRs in peregrine falcon eggs have evolved over time, reflecting broader regulatory and industrial shifts that have occurred in response to the environmental risks posed by these compounds.

Geographically, there is a clear disparity in BFR contamination levels between peregrine falcon eggs from North America and Europe. For instance, eggs collected from Canada exhibited significantly higher concentrations of Σ16PBDE (the sum of 16 PBDE congeners) compared to those from Spain [182]. This difference can be attributed to the historical use and release patterns of PBDEs in these regions, with North America having a more significant prevalence of these chemicals prior to the phaseout of certain formulations [189]. Notably, BDE-153 was identified as the dominant congener, being present in more than 60% of the peregrine eggs studied, underscoring its persistent and bioaccumulative nature.

The persistence of BDE-153 in the environment can be explained by its longer half-life compared to other PBDE congeners, which allows it to accumulate to higher concentrations within the food web [174]. Furthermore, BDE-153 may also accumulate as a debromination product from higher brominated compounds, such as BDE-209, indicating a complex relationship between various PBDE congeners in the environment. This phenomenon is particularly pronounced in terrestrial food chains, which likely explains why peregrine falcons with a terrestrial diet in Canada demonstrated higher concentrations of BDE-153 than their counterparts in Spain [182].

The analysis of BFR congener profiles in peregrine falcon eggs revealed important differences based on geographic location and dietary habits. In Canadian peregrine eggs, BDE-47 constituted a more substantial proportion of the ΣPBDEs, particularly in falcons with a terrestrial diet, while BDE-183 was more prevalent in the eggs of peregrines that fed on aquatic prey. This pattern reflects the various exposure pathways depending on the feeding habits of the birds and underscores the necessity of considering both geographical location and diet when assessing contaminant burdens in wildlife [182].

Interestingly, while newer HFRs such as BTBPE and DBDPE have been detected in various environmental matrices in North America and Europe, their presence in peregrine falcon eggs remains significantly lower compared to PBDEs. This finding suggests that the environmental accumulation and biomagnification of these newer flame retardants in top predators like peregrine falcons may not yet be as pronounced as that of the phased-out PBDEs.

The regulatory landscape surrounding BFRs has changed dramatically in recent years, particularly with the addition of penta- and octaBDE to the Stockholm Convention in 2009. This agreement reflects a growing global recognition of the hazards posed by these chemicals. Studies analyzing BFR concentrations in peregrine falcon eggs from Greenland between 1986 and 2014 indicated an increase in PBDE levels; however, this increase was not statistically significant except for BDE-209 [190]. The trend shift from a significant increase to non-significant levels over time could reflect changes in methodological approaches or a potential slowdown in the increase following global regulations on PBDEs. Notably, BDE-209 concentrations in peregrine falcon eggs showed a significant annual increase, raising concerns about the persistence of this particular congener despite its recent regulation [172].

In contrast to the increasing trends in BDE-209, BB-153 concentrations demonstrated a significant decrease over the same period, suggesting that regulatory measures have been effective in reducing certain PBDEs [190]. The decreasing trend of BB-153 in peregrine falcon eggs, along with its inclusion in the Stockholm Convention, reflects a response to past contamination and suggests a positive trajectory in regulatory efforts. Similarly, HBCDD, which has been included in the Stockholm Convention since 2013, showed decreasing concentrations in some recent time-series studies, although the trends in peregrine falcon eggs remained non-significant [190].

Interestingly, despite the lack of statistical significance in increasing trends for compounds like dechlorane plus and other unregulated substances, their detection warrants attention for future research and risk assessment. The study also observed a significant decrease in DPTE, a compound with limited environmental data, between 1986 and 2014, suggesting that regulatory actions can potentially lead to a positive shift in contaminant levels [190].

Comparing studies of peregrine falcons and American kestrels highlights that both species are at risk from BFR exposure, although there are differences in their contamination levels and health outcomes. Extensive research on the American kestrel has revealed significant negative effects of BFRs, including thinner eggshells and reduced reproductive success, which may serve as a warning for peregrine falcons [191]. Given the ecological similarities between these two raptor species, the parallels in exposure and effects raise concerns that peregrine falcons could also be negatively impacted by BFRs.

The examination of BFRs in peregrine falcon eggs highlights critical insights into the complex interactions between environmental contaminants and wildlife health. Although research on peregrine falcons remains in its early stages, it is evident that BFRs present significant risks to these raptors, with geographical variations in contaminant levels reflecting historical usage patterns and regulatory responses. Additionally, the potential for emerging flame retardants to impact wildlife health underscores the need for ongoing monitoring and the assessment of environmental contaminants in avian species. The narrative surrounding BFRs in peregrine falcons serves as a poignant reminder of the importance of regulatory measures and research in protecting wildlife from the pervasive threat of environmental pollutants.

10. Future Directions

The peregrine falcon, with its majestic wingspan and impressive hunting prowess, has become a critical sentinel species for monitoring environmental contamination. As it soars at the top of the food chain, this remarkable bird not only captivates birdwatchers and conservationists but also serves as a vital indicator of ecological health. However, to harness the full potential of the peregrine falcon in environmental monitoring, future research might delve into several key areas. This exploration could be essential for enhancing our understanding of ecological threats and refining management strategies.

A significant focus for future research might involve expanding monitoring efforts to encompass a broader range of contaminants. Traditionally, studies have concentrated on well-known pollutants like organochlorine pesticides and heavy metals [15,45–48,84,96]. Yet, as our understanding of environmental toxins evolves, contaminants such as pharmaceuticals, personal care products, and nanomaterials have begun to emerge as serious concerns [17]. These substances are increasingly present in our ecosystems, accumulating in food webs and posing risks not only to wildlife but also to human health. To effectively use peregrine falcons as bioindicators, monitoring programs must adapt and integrate these new pollutants into their frameworks, ensuring that we can assess the ecological risks tied to their presence.

The marriage of advanced technologies with traditional monitoring approaches holds immense promise for enhancing our understanding of contaminant exposure and its physiological effects on peregrine falcons. Remote sensing technologies could play a pivotal role in tracing the origins of contaminants and mapping their dispersal across landscapes. Meanwhile, molecular biomarkers might shed light on the biological impacts of these pollutants at the cellular level [192]. By employing these cutting-edge tools, researchers can collect more precise and comprehensive data, ultimately supporting the development of effective conservation strategies tailored to protect peregrine falcons and their habitats.

Understanding the long-term effects of chronic exposure to low levels of pollutants is essential for safeguarding peregrine falcon populations. Longitudinal studies, which track the health and reproductive success of individual birds over time, might offer invaluable insights into how these factors influence population dynamics. Such research has the potential to illuminate the persistence of pollutants in ecosystems and their cumulative effects on avian health, helping to paint a clearer picture of the challenges faced by these magnificent birds.

The complexities of environmental contamination are not confined by borders, making collaboration with global monitoring networks increasingly important. By sharing data across regions, researchers can improve comparability and enhance their ability to track transboundary pollution sources [193]. This collaborative approach would provide a deeper understanding of how pollution impacts peregrine populations worldwide, informing conservation strategies that account for the interconnected nature of environmental threats.

In addition to pollution, peregrine falcons face a multitude of stressors, including climate change and habitat loss. Research should aim to explore the interactions between these stressors to understand their cumulative impacts on peregrine falcon populations. Developing holistic conservation approaches that consider these interconnected challenges is vital [194]. For instance, habitat degradation caused by climate change could amplify the detrimental effects of pollution, further threatening the survival of peregrines and other wildlife.

The growing awareness of the environmental impact of toxicants on human health has spurred significant research initiatives that aim to implement human semen as an early and sensitive biomarker for exposure to environmental pollutants while also assessing the quality of living environments [195–197]. Among the most promising research avenues emerging from this initiative might be the innovative use of semen analysis as a bioindicator of environmental pollution, particularly through the lens of peregrine falcons. By studying the semen of these majestic birds, researchers can gain invaluable insights into the contaminants affecting them, which also provides a critical link to human health data. This approach enhances our understanding of how pollutants influence reproductive health across different species, including our own.

Several key areas might warrant attention in this context:

a. The development of semen biomarkers: Identifying specific biomarkers within peregrine falcon semen that signal exposure to pollutants is crucial. Research should focus on how various contaminants influence semen quality, including sperm count, motility, morphology, and genetic integrity;
b. The assessment of reproductive health: Evaluating how pollutant exposure impacts reproductive success in peregrine falcons is essential. Studies should assess the correlations between semen quality and critical reproductive metrics, such as fertility rates, hatchling viability, and overall population health;
c. Integration with other indicators: Combining semen analysis with additional biological indicators, like tissue and blood chemistry, will yield a more holistic view of environmental contamination and its repercussions for peregrine falcons;
d. Longitudinal and multigenerational studies: Long-term studies tracking semen quality across generations will be vital for unraveling the chronic effects of pollution. This research should also examine how contaminants influence not only individual falcons but also their offspring;
e. Advanced analytical techniques: Employing advanced techniques such as mass spectrometry, genomics, and proteomics to analyze semen samples will enhance sensitivity and specificity in pollutant detection. Such technologies can provide deeper insights into how contaminants affect reproductive physiology at the molecular level [17];
f. Global collaboration and standardization: Establishing standardized protocols for semen collection and analysis across various regions will facilitate global monitoring and the comparison of pollution impacts. Collaborating with international research networks can address transboundary pollution issues and improve data reliability;
g. Policy and conservation implications: Translating research findings into actionable conservation strategies and regulatory policies will be crucial for mitigating the effects of environmental pollution on peregrine falcons and other wildlife. This includes developing best practices for pollution control and habitat management informed by semen bioindicator data;
h. Public awareness and education: Raising public awareness about the significance of semen analysis in environmental monitoring can foster greater support for conservation efforts. Educational initiatives should emphasize the role of protecting peregrine falcons and other sentinel species in promoting overall environmental and human health.

Incorporating peregrine falcon research into a One Health framework could significantly enhance our understanding of environmental contamination and its impacts on wildlife, ecosystems, and human health. The One Health approach underscores the interconnectedness of human, animal, and environmental health, positioning the peregrine falcon as an ideal species for monitoring these cumulative effects. By integrating peregrine falcons into a One Health surveillance system, researchers can foster collaboration among wildlife biologists, ecotoxicologists, public health experts, and policymakers. Combining data from peregrine falcon monitoring with human health metrics can reveal the shared impacts of pollution, leading to more effective interventions and preventive measures. This holistic view of environmental health reinforces the need to preserve biodiversity and ecosystem services as a means of safeguarding human health.

11. Conclusions

In conclusion, the peregrine falcon plays a crucial role as a sentinel species, significantly enhancing our understanding of environmental contamination and its broader implications for ecology and human health. To further this understanding, future research must prioritize expanding the scope of monitoring to include a wider array of emerging contaminants. By employing advanced technologies, researchers can improve the precision and depth of data collection, enabling a more thorough analysis of the pollutants affecting these magnificent birds. Longitudinal studies could be vital for uncovering the chronic effects of environmental toxins on peregrine falcon populations, particularly concerning their reproductive health and survival rates. Such research will reveal how persistent exposure impacts these raptors over time. Furthermore, global collaboration and data sharing will be essential in addressing transboundary pollution, ensuring that the findings are relevant across various regions and ecosystems. This interconnected approach will allow scientists to explore the complex interactions among multiple environmental stressors, offering a comprehensive view of their cumulative impacts on both peregrine falcons and the ecosystems they inhabit. The remarkable recovery of peregrine falcons serves as a testament to the success of regulatory measures aimed at reducing pollutants exposure, underscoring the importance of sustained conservation efforts. This recovery highlights the intricate connections between ecological factors and raptor populations, reminding us of the delicate balance between human activities and wildlife conservation.

Adopting a One Health approach further emphasizes the link between wildlife, humans, and environmental health. By recognizing the peregrine falcon as a critical bioindicator, we can inform conservation strategies and public health initiatives more effectively. Integrating data from falcon monitoring into broader environmental health frameworks will enhance our capacity to detect and mitigate contamination effects, ultimately supporting the preservation of biodiversity, ecosystem integrity, and human well-being for future generations.

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