Guardians of the Forest: European Badgers (*Meles meles*) as Bioindicators of Environmental Health

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Abstract. *The European badger (Meles meles), a widespread and adaptable mustelid native to Europe and parts of Asia, has emerged as a valuable sentinel species for monitoring environmental health. This review compiles multidisciplinary evidence demonstrating the utility of badgers as bioindicators for environmental contamination, antimicrobial resistance (AMR), and zoonotic diseases. Their omnivorous diet, frequent soil contact, and proximity to human-modified landscapes facilitate exposure to a range of ecological stressors. This review summarizes studies conducted across Europe from 2003 to 2022 that have detected numerous contaminants in badger tissues, including heavy metals (e.g., cadmium, lead, mercury), trace elements, and persistent organic pollutants, highlighting localised environmental pollution. Badgers have also been shown to harbour antibiotic-resistant bacteria such as Escherichia coli, Staphylococcus aureus, and Enterococcus spp., often carrying resistance genes like SHV-12, vanA, and tet(B), suggesting their role in tracking environmental AMR spread. Additionally, badgers serve as reservoirs or incidental hosts for various zoonotic pathogens, including Mycobacterium bovis, Leptospira interrogans, Toxoplasma gondii, and Borrelia burgdorferi. The synthesis of this evidence supports the use of M. meles in One Health frameworks as a practical tool for assessing ecological risks and guiding public health and conservation strategies.*

Introduction

The European badger (*Meles meles*) is a robust and adaptable mammal belonging to the Mustelidae family, order Carnivora. It possesses a distinctive appearance with a grizzled grey dorsal coat, dark ventral fur, and characteristic black and white facial stripes (Byrne et al., 2012). Badgers are primarily nocturnal, engaging in most of their foraging and social behaviours after dark. It holds a conservation status of “Least Concern” on the IUCN Red List, attributed to its extensive distribution and stable population across Europe and parts of Asia, thriving in varied environments thanks to its generalist diet, behavioural adaptability, and tolerance to human-modified landscapes (da Silva et al., 1993). They construct and inhabit extensive burrow systems known as setts, which can be quite elaborate and are often used communally. On average, they often live in groups of six adults, though associations as large as 23 individuals have been documented (Revilla and Palomares, 2002; Roper, 1992). Their preferred habitats are those offering moderate moisture, rich pastures, and sufficient cover, including tree-, shrub-, or rock-dense areas ideal for concealment and burrow placement. It has an omnivorous and opportunistic diet, with its primary food source including terrestrial worms, especially earthworms (Goszczyński et al., 2000). They also consume a wide range of animal foods, including insects, molluscs, small mammals (like rabbits), birds, reptiles, amphibians, carrion, and even fish. In addition to animal prey, badgers also feed on plant materials, such as roots, tubers, fruits, seeds, nuts, and fungi (Cleary et al., 2009).

Eurasian badgers interact with human environments in both beneficial and problematic ways. On the positive side, they help control populations of wasps and hedgehogs, and their burrows contribute to biodiversity by providing shelter to other animals (Griffiths and Thomas, 1993)and in all states of Europe west of the border with the former Soviet Union. Within this area it is absent only from the arctic zones, high-altitude areas, and some islands. The Badger is currently a protected species in the UK, the Irish Republic, Spain, Portugal, Italy, Belgium, the Netherlands, Albania, Greece, Estonia, Luxembourg and Hungary, but Luxembourg and Hungary are to reconsider protected status. Elsewhere, the species is either considered as small-game or as a pest, hunting being regulated by closed seasons. At present Finland and Burgenland (Austria. Commercially, badger hair is used in brush-making, and badger hides are occasionally used in textiles. Conversely, they can cause damage to crops, fruit gardens, and property structures through their burrowing activities. They sometimes prey on poultry and are a reservoir for bovine tuberculosis (bTB), a disease that can

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be transmitted to cattle, resulting in significant economic losses for farmers (Cassidy, 2019). Despite their classification as Least Concern by the IUCN, local population densities can vary significantly and may be negatively affected by urban development, road mortality, and disease outbreaks, necessitating regional conservation monitoring (Fig. 1) (Fabrizio et al., 2019; Jenkinson and Wheater, 1998)and on the number of illegal disturbance events recorded over the study period. The number of, and distance from, public accesses did not influence sett persistence, and the least frequently disturbed setts (i.e. those with an average of one or less disturbance incidents every 2 years.

Because the European badger is widely distributed across various habitats, consumes a broad and varied diet, and often inhabits areas near human activity, it has the potential to serve as a sentinel species (Board on Environmental Studies and Toxicology et al., 1991). A sentinel species is used to detect and monitor the presence and impact of environmental contaminants within its habitat (Fig. 2) (Ozimec et al., 2015). Through the study of badgers, researchers can identify ecological threats such as infectious agents or other human-induced hazards. This makes the badger a valuable indicator for assessing risks to local wildlife populations, ecosystems, and potentially even human health (Goretti et al., 2018). This work aims to compile the studies that use the *Meles meles* as a sentinel species.

Materials and nethods

The initial search on the Web included terms used in combination or isolation, such as “badger”, “European”, “*Meles meles*”, “pesticides”, “pollution”, “contamination”, “antibiotics”, “zoonises”, yielding articles from digital databases (Web of Science, Scopus, PubMed, SciELO, Research Gate, Google Scholar). The inclusion/exclusion steps were independently reviewed by the two authors of the paper. Only papers in which the species, country, year, and agent were available were included. Another selection criterion

Fig. 1. European badgers (*Meles meles)* were admitted to the wildlife rehabilitation centre for several reasons, such as collisions with vehicles or entrapment

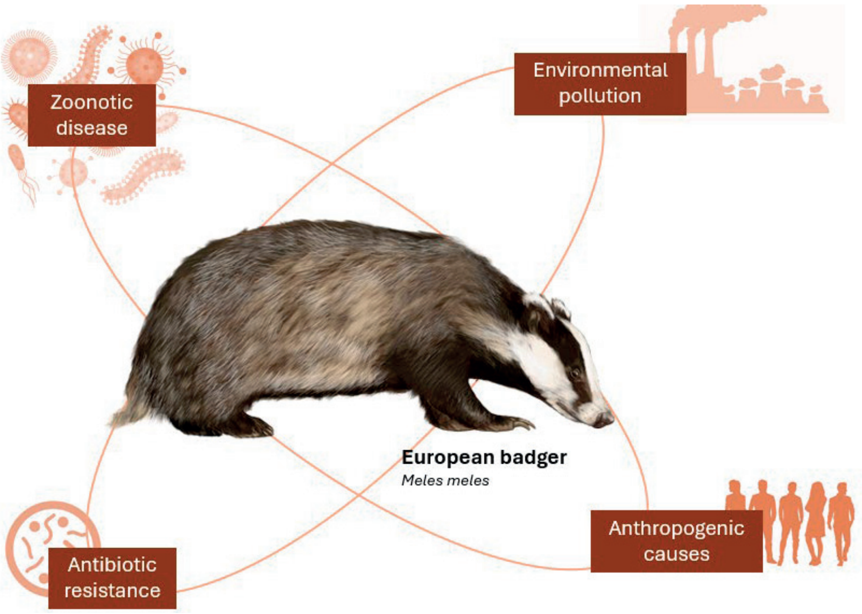

Fig. 2. Meles meles as a bioindicator sentinel of environmental ecosystem health (Author: Andreia Garcês)

was language, with only manuscripts in English, Portuguese, Spanish, and French being considered.

European badgers as a sentinel of environmental contamination

European badgers have been increasingly recognised as effective bioindicators of environmental pollution due to their wide distribution, omnivorous diet, and close interaction with the soil (Cleary et al., 2009; Mullineaux et al., 2021). Table 1 presents a review of various studies evaluating environmental contaminants found in European badgers across multiple countries. It summarises key information, including country, years of data collection, sample types analysed, contaminants identified, concentrations measured, and references to the original studies. Data spans from 2003 to 2022, covering nearly two decades of research across various European countries, including Croatia, the Czech Republic, Spain, Poland, Northern Ireland, the United Kingdom, and Italy (Mateo et al., 2012; Ozimec et al., 2015; Squadrone et al., 2022), highlight the accumulation of multiple contaminants in badger tissues such as liver, kidney, muscle, diaphragm, hair, and even tumoUrs (Table 1). The contaminants analysed span a broad spectrum, including heavy metals (e.g., cadmium, lead, mercury), metalloids (arsenic, selenium), trace elements (aluminium, chromium, copper, zinc), and organic pollutants (organochlorine pesticides and polychlorinated biphenyls or PCBs). Concentrations vary significantly by country, tissue type, and pollutant. Notably high levels of cadmium and zinc were found in the kidneys and livers of Spanish badgers (García-Muñoz et al., 2023), while Italian badger hair revealed high levels of aluminium and iron, suggesting significant environmental exposure (Squadrone et al., 2022). The use of different tissues provides insight into both short- and long-term exposure. Hair, for example, reflects chronic accumulation, while organs like the liver and kidneys indicate more recent or active exposure. Spain reported a wide variety of persistent organic pollutants, including DDE, DDD, Mirex, and several PCB congeners, some of which were found in relatively high concentrations, highlighting localised pollution.

Badger as a sentinel of antimicrobial resistance (AMR)

Table 2 compiles documented findings on antibiotic-resistant bacteria isolated from European badgers, showcasing their potential role as sentinels for environmental antimicrobial resistance (AMR) (O'Hagan et al., 2021). The studies performed from 1997 to 2019 across several European countries, including Ireland, Spain, Poland, Germany, and England, reveal the presence of a wide array of antibiotic-resistant bacteria in badger populations, isolated from faecal, nasal, rectal, and pharyngeal swabs (Osińska et al., 2020). *Escherichia coli* is the most frequently isolated and resistant species, with widespread resistance to beta-lactams (AMP, CZA, CTX), fluoroquinolones (CIP, N), aminoglycosides

Table 1. Review of articles that evaluated environmental contaminants in European badgers (*Meles meles*) regarding the number of animals, substance type, year, sample type analysed, and country

Country	Year	Type of sample	Substance	Concentration	References
Croatia	2009–2010	Muscle, liver, and kidney	As	0.0034 mg/kg, w.w.	(Bilandžić et al., 2012)
			Cd	0.009	
			Cu	2.99	
			Hg	0.005	
			Pb	0.077	
Czech Republic	2011	Liver, kidney, muscle, diaphragm, tumour	As	0.07; 0.02; 0.02; 0.03	(Bukovjan et al., 2014)
			Cd	1.09; 2.06; 0.10; 0.67	
			Cr	0.46; 0.31; 0.12; 0.16	
			Cu	9.47; 5.81; 0.17; 7.74	
			Hg	0.49; 0.67; 0.01; 0.36	
			Pb	2.98; 1.69; 0.26; 0.67	
			Zn	36.20; 28.30; 17.311; 44.54	
Spain	2020–2022	Liver, kidney	Zn	179; 164	(García-Muñoz et al., 2023)
			Hg	0.77; 1.16	
			Cd	4.70; 7.61	
			Pb	0.45	
			As	0.14; 0.08	
Poland	2003–2005	Kidney, liver, pectoral muscle	Hg	0.38; 0.64; 0.25	(Kalisińska et al., 2009)

Table 1 cont.

Country	Year	Type of sample	Substance	Concentration	References
Spain	2004–2006	Liver	HCB	< 0.01	(Mateo et al., 2012)
			b-HCH	0.48	
			a-Heptachlor epoxide	< 0.01	
			a-Heptachlor epoxide	< 0.01	
			b-Heptachlor epoxide	< 0.01	
			p,p^{0} -DDE	36.3	
			p,p^{0} -DDD	5	
			Mirex	84.2	
			PCB 28–31	> 0.01	
			PCB 101	> 0.01	
			PCB 118	1.09	
			PCB 153	12.3	
			PCB 105	> 0.01	
			PCB 138	0.21	
			PCB 126	0.87	
			PCB 128	25.1	
			PCB 156	< 0.01	
			PCB 180	< 0.01	
			PCB 169	65	
			PCB 170	< 0.01	
North Ireland	2017–2018	Liver, muscle, and kidney	Al	6.2; 12.47; 17.41	(Mullineaux et al., 2021)
			As	1.2; 1.2; 1.2	
			Cr	1.3; 2.37; 1.67	
			Cu	77.61; 12.81; 25.83	
			Mo	3.18; 1.4; 1.41	
			Ni	1.39; 1.44; 3.68	
			Pb	1.21; 1.2; 1.47	
			Se	4.22; 1.2: 8.2	
			Sr	0.35; 0.15; 0.54	
			Zn	113.39; 166.16; 83.08	
Croatia	2009–2011	Muscle, kidney, liver	Cd	0.074; 3.046; 0.395	(Ozimec et al., 2015)
			Pb	0.131; 0.190; 0.197	
United Kingdom	2017–2017	Liver	Ag	0.0381	(Sartorius et al., 2023)
			Al	8.37	
			As	0.0906	
			B	1.63	
			Ba	0.487	
			Be	0.0257	
			Ca	286	
			Cd	3.37	
			Co	0.149	
			Cr	0.894	

Table 1 cont.

Country	Year	Type of sample	Substance	Concentration	References
United Kingdom	2017–2017	Liver	Cs	0.00707	(Sartorius et al., 2023)
			Cu	32.0	
			Fe	1160	
			K	8140	
			Mg	596	
			Mn	16.0	
			Mo	2.54	
			Na	3930	
			Ni	0.145	
			P	9020	
			Pb	1.38	
			Rb	6.45	
			S	8590	
			Se	3.05	
			Sr	0.328	
			Ti	105	
			Tl	0.0143	
			U	0.00235	
			V	0.282	
			Zn	127	
Italy	2022	Hair	Al	849 ± 51	(Squadrone et al., 2022)
			As	1.1 ± 0.22	
			Cd	0.023 ± 0.001	
			Cr	2.5 ± 0.12	
			Cu	52 ± 0.43	
			Fe	852 ± 62	
			Hg	0.52 ± 0.019	
			Mn	27 ± 1.4	
			Ni	1.7 ± 0.84	
			Pb	0.83 ± 0.054	
			Pd	< LOQ	
			Pt	0.011 ± 0.001	
			Rb	1.0 ± 0.14	
			Sn	0.051 ± 0.001	
			V	1.6 ± 0.16	
			Zn	131 ± 10	

HCB – Hexachlorobenzene; PCB – Polychlorinated biphenyls; DDE – Dichlorodiphenyldichloroethylene; DDD – Dichlorodiphenyldichloroethane; Cr – Chromium; Cu – Copper; Ni – Nickel; Pb – Lead; Zn – Zinc; Cd – Cadmium; Mn – Magnesium; Hg – Mercury; Al – Aluminum; Ca – Calcium; Fe – Iron; Mg – Magnesium; As – Arsenic; Sr – Strontium; Am – Americcium; Cs – Caesium; Pu – Plutonium; Co – Cobalt; V – Vanadium; Rb – Rubidium; Pt – Platinum; Sn – Tin; Tl – Thallium.

Table 2. Antibiotic resistance in European badgers (*Meles meles*) regarding species, country, year, type of sample, bacteria isolated, antibiotic resistance and resistance genes

Specie	Country	Year	Type of sample	Isolated bacteria	Antibiotic resistance*	Resistance genes	Ref.
Badger (*Meles meles*)	Ireland	2018–2019	Faecal, nasopharyngeal swabs	*Salmonella spp.*, *E. coli*	AMP, CZA, CEP, CTX	–	(O'Hagan et al., 2021)
	Spain	2016–2017	Swabs	*E. coli*	CIP, N, C, S, T	*SHV-12*	(Darwich et al., 2019)
	Poland	2014–2018	Rectal swabs	*E. coli*	AMP, S, KAN, C, CIP, S, N, TE	*aph(3¢)-Ia, strA, aph(3¢)-Ia, sul2, tetA, tetB, fbR, cat, sul3*	(Osińska et al., 2020)
	Germany	2011	Pharyngeal swab	*S.aureus*		*gapA, katA, CoA, Spa, sbi, nuc1, sarA, saeS, vraS, agrl, hid,*	(Monecke et al., 2013)
	Spain	2015–2015	Faecal	*E. coli*	AMP, TE	*Tet(B)*	(Alonso et al., 2017)
	Spain	2012–2015	Nasal and rectal swabs	*Staphylococcus* spp.	N, P, FOX, FA, CLI		(García et al., 2020)
	England	1997 to 2000	Faecal	*Enterococcus* spp.	VAN, TEC	*vanA*	(Mallon et al., 2002)

AMP – ampicillin; E – erythromycin; CD – clindamycin; CEF – ceftiofur; CEP – cephalothin; CPN – cephalexin; CTX – cefotaxime; TE – tetracycline, N – nalidixic acid; CIP – ciprofloxacin; KAN – kanamycin; VAN – vancomycin; FA – fusidic acid; P – penicillin; TEC – tobramycin; FOX – cefoxitin.

(KAN), tetracyclines (TE), and other antibiotic classes (Darwich et al., 2019). Genetic analysis revealed important resistance genes such as *SHV-12* (an extended-spectrum β-lactamase), *tet(B)* (tetracycline resistance), and multiple mobile resistance elements like *aph(3')-Ia, sul2, fbR,* and *cat*. Resistance genes such as *SHV-12*, *vanA*, *tet(B)*, and various plasmid-borne genes were detected, indicating potential for horizontal gene transfer. Of particular concern is the detection of *vanA* in *Enterococcus spp.* in England, conferring resistance to vancomycin, a last-resort antibiotic in human medicine (Mallon et al., 2002). Additionally, virulence and regulatory genes in *Staphylococcus aureus* (e.g., *spa*, *sarA*, *vraS*) suggest the presence of potentially pathogenic strains in the badger population (Monecke et al., 2013).

Badgers as a sentinel of zoonotic diseases

Wild animals can act as sentinels for the current health status of the ecosystems they inhabit. The European badger serves as an effective sentinel species for monitoring the presence and circulation of zoonotic pathogens in the environment. As omnivorous mammals with wide-ranging ecological niches – from woodland and farmland to peri-urban areas – badgers are exposed to a variety of infectious agents. Their scavenging behaviour and frequent contact with soil, water sources, and potentially contaminated prey increase their likelihood of acquiring and harbouring zoonotic pathogens. Badgers have been identified as natural reservoirs or incidental hosts for several zoonoses of public and veterinary health importance, including *Mycobacterium bovis* (the causative agent of bovine tuberculosis), *Leptospira* spp., *Toxoplasma gondii, Echinococcus multilocularis,* and *Trichinella* spp. Due to their relatively stable home ranges and long life span, badgers accumulate exposure to pathogens over time, making them valuable indicators of local and persistent infection risks. Their proximity to livestock and human settlements in many areas also raises concerns about the potential for spillover. Surveillance of zoonotic agents in *Meles meles* populations can thus provide early warning signals for emerging threats, support risk assessments, and contribute to the implementation of One Health strategies aimed at managing diseases at the human–animal–environment interface. While the list of pathogens associated with badgers continues to evolve, Table 3 provides a summary of zoonotic agents identified in the European badger *(Meles meles).*

Discussion

The European badger (*Meles meles*) emerges as a compelling sentinel species for evaluating the health of European ecosystems. Its wide distribution, omnivorous diet, longevity, and close association with soil and human-modified environments place it at the intersection of ecological, public, and veterinary health (da Silva et al., 1993). The present review consolidates a growing body of evidence demonstrating the value of badgers in monitoring environmental contaminants, antimicrobial resistance

(AMR), and zoonotic pathogens – three pillars of One Health surveillance.

Exposure of badgers to heavy metals, metalloids, and persistent organic pollutants (POPs) provides

Table 3. Zoonotic bacteria isolated from European badger (*Meles meles*)

Bacteria		
Mycobacterium bovis	Culture-confirmed infections from lymph/tissue in several countries	(Blanco Vázquez et al., 2021)
Mycobacterium avium subsp. avium & paratuberculosis	Isolated from lymph nodes in Central Italy	(Blanco Vázquez et al., 2021)
Salmonella enterica	Faecal carriage in UK and Italian populations	(Gambi et al., 2022)
Leptospira interrogans	50 % seroprevalence in Andalusia, Spain; antibodies in Slovenia	(Blanco Vázquez et al., 2021)
Anaplasma phagocytophilum	PCR-positive blood/spleen from nine European countries	(Lindhorst et al., 2024)
Ehrlichia spp.	Same continental survey (low prevalence)	(Lindhorst et al., 2024)
Candidatus Neoehrlichia spp.	First detected in badger blood, Hungary	(Hornok et al., 2017)
Borrelia burgdorferi	DNA recorded in badgers/ticks	(Lindhorst et al., 2024)
Rickettsia spp.	Molecular detections in continental survey	(Lindhorst et al., 2024)
Bartonella spp.	Multiple European detections	(Lindhorst et al., 2024)
Coxiella burnetii	Targeted and PCR-positive in some UK studies	(Guardone et al., 2020)
Francisella tularensis	Screened in the UK badgers; considered a risk host	(Guardone et al., 2020)
Virus		
Rabies	Occasional spill-over	(Margalida and Colomer, 2012)
Coronavirus	Discovered in Italian carcasses	(Zamperin et al., 2023)
Caliciviridae	Whole genome from Hungarian badgers	
Badger gammaherpesvirus	Higher viraemia variant reported in 2022	(Tsai et al., 2022)
Protozoaria		
Giardia duodenalis	Zoonotic genotypes in 49% of badgers in Central Italy	(Guardone et al., 2020)
Cryptosporidium spp.	Oocysts in 23% of the same study population	(Maestrini et al., 2022)
Babesia sp. badger types A–C (B. microti group)	Up to 89% prevalence; close relatives infect humans	(Guardone et al., 2020)
Toxoplasma gondii		(M et al., 2018)
Sarcocystis spp.		(K et al., 1994)
Trypanosoma pestanai		(G et al., 2021)
Ectoparasites		
Ixodes ricinus, I. canisuga, I. hexagonus, I. reduvius, I. melicula		(Guardone et al., 2020)
Mange mites (Sarcoptes spp., *Demodex* spp.)		(Mullineaux and Keeble, 2016)
Helminths and other		
Trichinella britovi	Muscle larvae in the Romanian badger	(Z et al., 2020)
Diroflaria immitis, D. repens	PCR detections across Europe	(Lindhorst et al., 2024)
Thelazia callipaeda	Romanian badger	(Ionică et al., 2019)
Strongyloides stercoralis		(Maestrini et al., 2022)
Eucoleus spp.	Eggs found in faeces; occasional human cases reported	(M et al., 2023)

Table 3 cont.

Fungi		
Trichophyton mentagrophytes	Dermatophytosis confirmed in badgers in Germany, the UK, and the Czech Republic. Lesions observed.	(Segal and Elad, 2021)
Microsporum canis	Occasionally isolated or suspected in badgers via dermatomycoses and contact with domestic animals in Europe.	(Segal and Elad, 2021)

a unique window into localised and long-term environmental contamination (Sartorius et al., 2023). Across Europe, toxic elements such as cadmium, lead, mercury, arsenic, and aluminium have been consistently detected in multiple tissues, with considerable inter-country variability. For instance, Spanish badgers exhibit markedly high concentrations of cadmium and zinc in liver and kidney tissues, while Italian specimens display elevated levels of aluminium and iron in hair, suggesting chronic exposure to industrial pollutants. Notably, the diversity of sampled matrices (liver, kidney, hair, muscle, and even tumours) enhances interpretative depth (Bukovjan et al., 2014), enabling both temporal and tissue-specific insights into pollutant bioaccumulation. Hair sampling, in particular, offers a non-invasive avenue for long-term exposure assessment, applicable to ongoing biomonitoring protocols. Furthermore, the detection of PCBs, DDT metabolites (DDE, DDD), and other organochlorines underscores the vulnerability of badgers to legacy contaminants still circulating in European landscapes despite regulatory bans (Alleva et al., 2006; Florijančić et al., 2013; Kalisińska et al., 2009).

Badgers also serve as reservoirs for antibiotic-resistant bacteria, underscoring their role in tracking environmental AMR dissemination. The presence of multidrug-resistant *Escherichia coli, Staphylococcus aureus, Salmonella* spp., and *Enterococcus* spp. in badger swabs from countries including Ireland, Spain, and Poland reflects a significant environmental burden of antimicrobial residues and resistant pathogens (Alonso et al., 2017; Gambi et al., 2022; Monecke et al., 2013). Detection of clinically relevant resistance genes such as *SHV-12, tet(B), and vanA* – the latter conferring vancomycin resistance – raises concern about horizontal gene transfer in the wild and potential spillover into livestock and human populations (Mallon et al., 2002; Monecke et al., 2013). Furthermore, findings of virulence genes (e.g., *sarA, vraS*) in *S. aureus* suggest the presence of pathogenic strains with potential zoonotic implications (Garcia, 2017). These results highlight the necessity of incorporating wildlife into integrated AMR surveillance frameworks, particularly in rural-urban interface zones (Dolejska, 2020).

The extensive catalogue of zoonotic agents isolated from *Meles meles*, ranging from *Mycobacterium bovis* and *Leptospira interrogans* to *Toxoplasma gondii* and *Trichinella britovi*, reaffirms the ecological role of badgers as a disease reservoir and sentry species (Corner et al., 2011; M et al., 2018; Žele-Vengušt et al., 2021). Several of these pathogens pose a dual threat to livestock productivity and human health, reinforcing the value of badgers in early warning systems for zoonoses. In particular, the consistent association of badgers with bovine tuberculosis across Europe warrants continued monitoring, especially given their overlapping habitats with cattle. The presence of other vector-borne pathogens such as *Anaplasma phagocytophilum, Babesia* spp., and *Borrelia burgdorferi* (Lindhorst et al., 2024) further positions badgers within complex vector–host–pathogen networks that require multi-sectoral management approaches. The detection of emerging viruses and protozoa in recent years suggests that badgers may also serve as sentinels for novel or re-emerging infectious agents in the European biome (Hornok et al., 2017).

The integration of badgers into One Health surveillance can support risk assessment and policy development for environmental protection, disease control, and antimicrobial stewardship. Veterinarians, particularly those working in wildlife rehabilitation, public health, or livestock management, are uniquely positioned to contribute to and benefit from badger-based sentinel data. Surveillance findings may inform land use decisions, livestock vaccination strategies, and zoonosis mitigation programmes, especially in regions where badger–livestock–human contact is frequent (Bezerra-Santos et al., 2021; Letková et al., 2006). Nevertheless, challenges remain. Standardisation of sampling protocols, harmonisation of contaminant reporting metrics, and the development of longitudinal studies are necessary to improve cross-regional comparability. Ethical and logistical considerations related to badger handling, particularly in protected areas or disease control contexts (e.g., bTB culling programmes) (Corner et al., 2011; Osińska et al., 2020) must also be addressed with sensitivity to local regulations and public perception (Aranaz et al., 2004).

Despite the growing recognition of *Meles meles* as a valuable sentinel for One Health surveillance, several knowledge gaps limit its full application across Europe. A key constraint is the lack of standardised sampling and analytical protocols. Studies differ in the biological matrices analysed and laboratory techniques used, hindering cross-country comparisons and the establishment of continental baselines for pollutants, antimicrobial resistance (AMR), and zoonotic pathogens. Developing harmonised methods and centralised data repositories is, therefore, essential to enable consistent spatial and temporal analyses (Aranaz et al., 2004). Most current research provides cross-sectional data, with limited longitudinal monitoring to track temporal trends in contaminant bioaccumulation or pathogen prevalence. Long-term, non-invasive monitoring, using matrices such as hair, faeces, or environmental DNA, would improve understanding of chronic exposures and seasonal variation. Similarly, while AMR has been detected in badgers, the ecological and behavioural pathways driving resistance acquisition and transmission remain poorly understood. Integrating metagenomic and resistome analyses could clarify links between wildlife, livestock, and human environments (Corner et al., 2011; Osińska et al., 2020).

The role of badgers in emerging zoonoses also warrants deeper investigation. Surveillance should be expanded to include novel and re-emerging pathogens using molecular and serological tools, alongside modelling of badger–vector–pathogen interactions under changing climatic and land-use conditions. Additionally, research has been geographically biased toward Western Europe, leaving Eastern and Northern regions underrepresented despite differing environmental pressures and management practices. Finally, ethical and social challenges surrounding badger research, particularly in tuberculosis control contexts, require attention. Promoting non-lethal sampling and understanding public attitudes toward wildlife surveillance will be key to sustainable monitoring strategies. Addressing these gaps through coordinated, interdisciplinary research will strengthen the integration of badgers into One Health frameworks and enhance their value as indicators of environmental and public health (Bezerra-Santos et al., 2021; Letková et al., 2006).

Conclusion

Eurasian badgers offer a versatile and ecologically relevant model for monitoring environmental health. Their utility as sentinels of pollution, AMR, and zoonotic disease underlines their importance in multidisciplinary One Health strategies. Continued investment in wildlife surveillance infrastructure and intersectoral collaboration will be essential to harness the full potential of *Meles meles* in safeguarding both ecosystem and public health.

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