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SHORT RESEARCH AND DISCUSSION ARTICLE

A bibliometric analysis: what do we know about metals(loids) accumulation in wild birds?

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Abstract

Metals and metalloids pollution is an important worldwide problem due to the social and ecological effects and therefore has been the subject of many disciplines and the adverse impacts have been documented. In this study, content analysis and trends of studies focused on heavy metal accumulation in birds were presented. For this purpose, a bibliometric network analysis of the studies that use the concepts of "pollution," "heavy metal," and "birds" together in the abstract, keywords, and titles of the papers was carried out. The purpose of choosing this research method was summarizing the relation between birds and environmental pollution in an understandable manner to determine metals(loids) pollution, which become an important environmental problem. Bibliometric data consisting of approximately 971 papers were evaluated with VOSviewer program using the network analysis method to answer the research questions. The results revealed that birds act as bioindicators in the determination of environmental pollution and that the contaminant metals deposited in the various tissues of birds provide preliminary information about environmental pollution. The most of bird studies emphasized that the metal accumulation was mostly in the liver, kidneys, and feathers and the accumulation caused serious problems in most of the vital activities of the birds. The USA is in the leading country in birds-heavy metal studies followed by Spain, Canada, and China. In addition, the mercury (Hg) was the most extensively studied heavy metal in these studies.

Keywords Bibliometric network analysis · Metals(loids) · Pollution · Birds · VOSviewer · Scopus database

Introduction

Metal(loid)s pollution caused by the increased industrial and industrial-oriented productions (Adriano 2001) has become a major problem for many species and environments in the last century (Rolli et al. 2015), especially for human beings (Nardiello et al. 2019). However, increasing human pressure and industrial waste led to heavy metal contamination of soil and water resources (Elbaz et al. 2010; Singh and Prasad 2011). This pollution can often be toxic or sufficient to cause death (Kakkar and Jaffery 2005; Nagajyoti et al. 2010; Newth et al. 2013; Sardar et al. 2013; Zeitoun and Mehana 2014). Heavy metals that cause pollution of the biosphere have become a worldwide ecological problem (Jamal et al. 2013); therefore, many studies have been carried out in different branches of the science (Adriano 2001; Burger and Gochfeld 2000; Dauwe et al. 2004; Ding et al. 2020; Durmus 2018; Durmuset al. 2018; Dushenkov et al. 1995; Eeva et al. 2009; Morton-Bermea et al. 2009; Sharma et al. 2008; Singh et al. 2010; Türkdogan et al. 2003; Yang and Sun 2009).

Metal pollutants that accumulate in nature may have mortality, toxicity, or morbidity effects on wildlife (Newth et al. 2013; Pain 1992; Scheuhammer 1987; Scheuhammer and Norris 1996). Birds, which are the important members of the wildlife, have a very high mobility (Callens et al. 2011) and thus are ideal creatures to study pollutant levels in large geographic areas (Bauerová et al. 2020; Burger and Gochfeld 1993, 2000; Burger 1994, 2006; Carneiro et al. 2015; Dauwe et al. 1999; Dauwe et al. 2005; Evers et al. 1998).

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The sensitivity of birds to environmental variables (Dauwe et al. 2000; Sidra et al. 2013) enables birds to react faster to even the slightest degradation in the environment. Leaving the area is the most common reaction of birds to the environmental degradation (Kiziroğlu 2001).

The IUCN report indicated that approximately 14% of current bird species are under global threat (IUCN 2020). About 1.9% of these species are threatened by anthropogenic pollution, especially metal pollution (BirdLife International 2018; Ding et al. 2020).

The objective of this study is to reveal the content analysis and trends of studies on heavy metal accumulation in birds. In this context, articles that establish a relationship between heavy metal pollution and birds and scanned in the Scopus database were subjected to bibliometric network analysis. Bibliometric review is a method used to increase research performance or to evaluate trends by identifying the publication characteristics such as author, subject, source, country, and citation (Polat et al. 2013; Small 2003). Citation analysis and content analysis are the common methods in bibliometric analysis (Sun et al. 2012). Many researchers from different disciplines have applied bibliometric analysis to reveal the trends in their studies (Clarke et al. 2007; Çelik 2020; Fourqurean et al. 2008; Kulak 2018; Kulak and Cetinkaya 2018; Kulak et al. 2019; Mao et al. 2010; Moreno-Opo and Margalida 2014; Pritchard 1969; Polat et al. 2013; Sun et al. 2012; Yang et al. 2015; Zhang et al. 2010).

The bibliometric analysis used in the study was conducted to learn the answers for the questions given below.

- Which methods come to the fore in studies on heavy metal pollution around the world?
- What are the factors causing heavy metal pollution?
- What is the main role of birds in heavy metal studies? What is the relationship between environmental pollution and birds? What is the history of the studies on bird and pollution?
- Which bird species come to the fore in the studies?
- Which organs of birds have been studied the most in the studies? What are the reasons?
- Which heavy metals come to the fore in the studies and what are the sources of these heavy metals?
- Which countries conducted the most studies on this field? What is the relationship between the numbers of publications and the industrial levels of the respective countries?
- What was the publication trend with time?

Materials and methods

Data source

The data were obtained from the online version of the Scopus database. This database indexes 38,060 current major journals by May 12, 2020. Scopus is recognized as the most comprehensive and reliable bibliographic resource (Kulak et al. 2019).

Source strategies

Many databases can be currently used to access information, bibliographic, or bibliometric research. The Web of Science (WoS), Scopus, Google Scholar, PubMed, MEDLINE, etc. are the most important of these databases (Chen 2017).

The major requirement of this study was the desire to reach more documents, which enabled to make comparisons between the databases. The same keywords were scanned in databases during the publication searching process and observations indicated that the Scopus source contains more documents than other databases. Scopus has a more heterogeneous layout as a database and offers a set of publications scanned from many different sources to the researchers (Ramalho et al. 2020). In addition to the aforementioned features, the Scopus provides significant convenience in obtaining the data to a researcher and the rich content was effective in the selection of the Scopus database for the study.

The document scanning process in the study was carried out in 3 steps using the TITLE-ABS-KEY filter.

- In the first step, “heavy metal” OR “heavy metals” OR “heavy metals and pollution” were scanned as the keywords and 184,935 studies come out (date of scan: 09/05/2020).
- In the second step, the search was carried out more specifically and articles containing the keywords “bird” OR “birds” OR “aves” were scanned and 4525 articles were reached (date of scan: 10/05/2020).
- In the third step, the abstracts of the studies on birds and, when necessary, the full texts were reviewed, and finally 971 studies directly related to the subject were recorded. The date range of the papers accessed was between 1970 and 2020 (scan date: 12/05/2020).

Lotka’s law

In order to assess the distribution of the number of articles reported by the researchers, we herein applied Lotka’s law of scientific productivity (Lotka 1926; Rousseau and Rousseau 2000).

Statistical analysis

Bibliometry is a powerful tool to analyze trends in scientific research in different disciplines (Glenisson et al. 2005). Bibliometric analyzes include publications on countries (Kulak et al. 2019; Çelik 2020), institutes (Moed et al. 1985; Li and Ho 2008), journals, and subject categories (Small 2003; Zhou et al. 2007) and describe the distribution patterns of citation analysis (McBurney and Novak 2002) and year-based citations (Slyder et al. 2011). VOSviewer is a network mapping software designed for visualization and easier understanding of the bibliometric data networks. The VOSviewer can be used to generate word repetition frequency, relationship status, country, author analysis, and citation network sets. The program provides a visualization of similarities (VOS) viewer service that enables detailed analysis of bibliometric maps (Van Eck and Waltman 2010). The software also provides zooming, scrolling, and search functions facilitating the detailed review of the created maps. Visual network maps produced in the VOSviewer program can be interpreted based on the frequency of repetition, relationship, clustering, and temporal trend.

Microsoft Excel was used for descriptive analyzes (country rankings, author profiles, number of articles, citation indexes, etc.) and the VOSviewer v.6.14 software (Van Eck and Waltman 2010) was used for analysis and visualization of the most frequently used terms (Fig. 1).

The detail of workflow for the study was presented in Fig. 2.

Results and discussion

Time trend analysis, type and language of publications

A total of 971 studies including metals(loids)-pollution-bird terms were included in this study. Articles (894 or 92.07%) are the most common type, followed by review (49 or 5.04%), conference paper (20 or 2.05%), technical note (5 or 0.51%), a short questionnaire or review (2 or 0.20%), and a book chapter (1 or 0.10%). The most common language used in the documents was English (932 or 95.98%) followed by Chinese (12 or 1.23%), Spanish (7 or 0.72%), German (6 or 0.61%), French (4 or 0.41%), Persian (4 or 0.41%), Polish (3 or 0.30%), and Portuguese (3 or 0.30%). The documents published between 1970 and 2020 were reviewed in this study. The number of annual publications significantly increased after 1995 and reached the peak with 47 articles published in 2018. The number of publications between 1974 and 1994 was fluctuated, and the number of articles published annually between 1995 and 2020 was almost constant at double digits (Table 1).

The number of documents published and the citations for each year were shown in Fig. 3 and Table 1. The highest percentage of annual citations to the total published documents was recorded in 1987 and 1992.

Co-occurrence network of terms

The interconnections and temporal trend of the terms used in the title and abstracts of the documents were shown in Fig. 4. Overall, 470 of the 15,120 terms met the criteria and the most relevant 269 (57%) terms were shown in Fig. 4 and Table 2. The terms were generally divided into 6 clusters, the terms used in the clusters were analyzed, and the trends in the studies were determined.

Seventy-four interrelated terms were identified in cluster 1 (red). The kidney organ (141 co-occurrence) among the 74

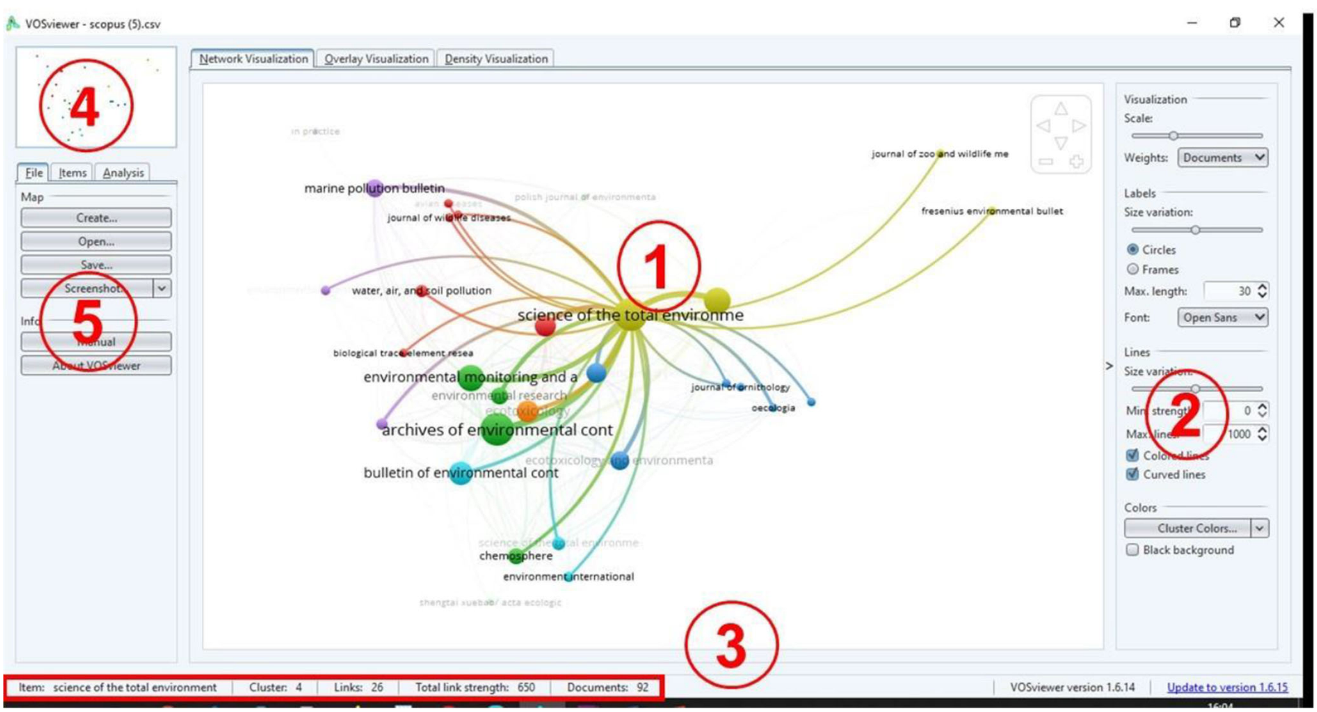

Fig. 1 Main window of VOSviewer. The numbers designate (1) main panel, (2) options panel, (3) information panel, (4) the overview panel, and (5) the action pane (according to van Eck and Waltman (2017), modified)

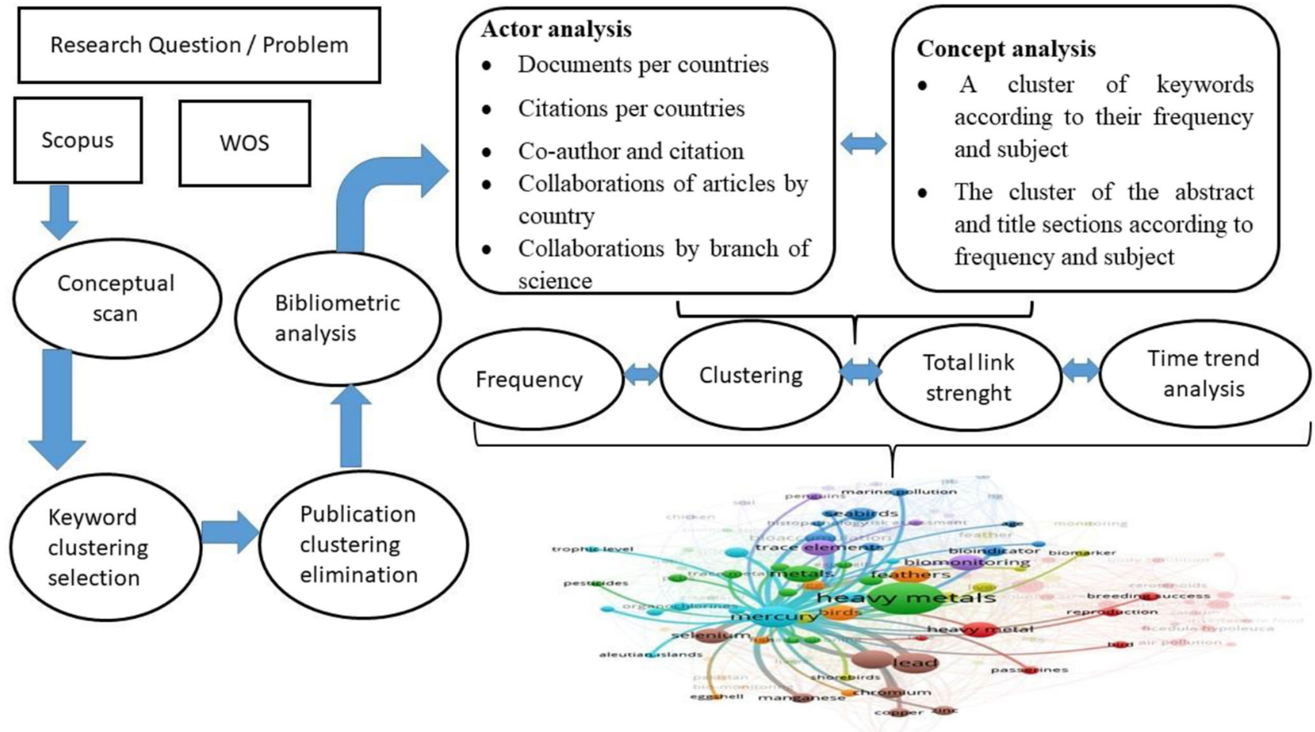

Fig. 2 Workflow chart of the study (according to Celik (2020), modified)

terms stands out as the highest co-occurrence term. The effects of metal(loid) pollution caused by human activity on birds were discussed in this cluster. The metals(loids) contents accumulated in various organs (lung, liver, kidney, heart, brain, muscle, feather, and egg) of birds were determined and the atomic absorption spectrometry (AAS) method was used to determine the heavy metal concentrations. The amount of heavy metals accumulated in various organs of songbird (house sparrow, rock pigeon), raptors (hawk), and heron (cormorant) bird species belonged to different ordos were measured. The most of the studies have concentrated on the kidney and the countries where such studies are carried out

Table 1 The number of documents and citation for each per year corresponding to the years between 1970 and 2020

Years	Doc.	Cit.	TCPD	Years	Doc.	Cit.	TCPD	Years	Doc.	Cit.	TCPD
1970	1	30	30.00	1989	7	131	18.71	2005	45	2127	47.27
1973	2	38	19.00	1990	8	93	11.62	2006	40	1301	32.52
1974	1	5	5.00	1991	7	55	7.85	2007	32	641	20.03
1976	2	49	24.50	1992	14	2023	144.50	2008	40	1269	31.72
1977	5	227	45.40	1993	16	448	28.00	2009	37	1431	38.67
1978	5	130	26.00	1994	7	333	47.57	2010	34	651	19.14
1979	7	195	27.85	1995	15	870	58.00	2011	36	884	24.56
1980	4	104	26.00	1996	18	698	38.78	2012	32	445	13.90
1981	7	290	41.42	1997	17	893	52.52	2013	29	605	20.86
1982	6	140	23.33	1998	20	1028	51.40	2014	44	701	15.93
1983	6	164	27.33	1999	22	1358	61.73	2015	34	513	15.08
1984	8	273	34.12	2000	25	1045	41.80	2016	22	207	9.40
1985	7	132	18.85	2001	20	759	37.95	2017	45	417	9.27
1986	10	396	39.60	2002	20	927	46.35	2018	47	227	4.82
1987	7	812	116.00	2003	42	1411	33.60	2019	45	105	2.34
1988	11	500	45.45	2004	39	1427	36.59	2020	22	3	0.13

TCPD, total citation per document, Cit./Doc. Cit., citations, Doc., documents

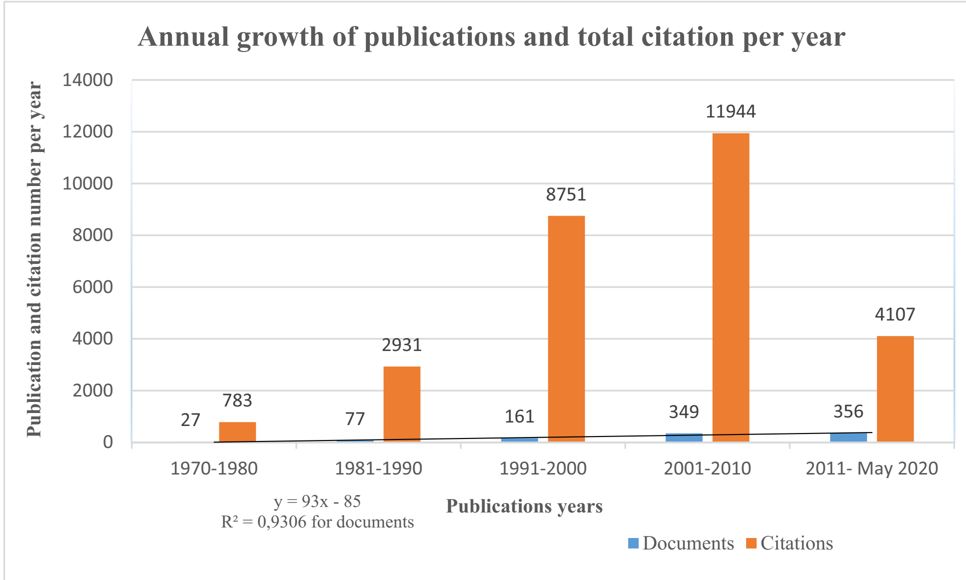

Fig. 3 Annual growth of publications and their total citations per year on heavy metal accumulation in birds (1970 to May 2020)

were Netherlands, Iran, Italy, Japan, India, Malaysia, and Pakistan, respectively (Fig. 4b, Table 2).

Seventy-two interrelated terms were identified in cluster 2 (green). The pollution (115 co-occurrences) stands out as the highest co-occurrence term among the 72 terms. Environmental and air pollution of heavy metals originating from industrial and industry-oriented factories were discussed in this cluster. The adverse impacts of these pollutants on the propagation activities of birds have been discussed. Nests of different bird species (*Milvus migrans*, *Ciconia ciconia*, *Parus major*, *Ficedula hypoleuca*, *Cyanistes caeruleus*) were investigated and some features of eggs were included in the studies along with blood samples taken from juvenile individuals. Spain stands out as the country where most of the studies on this field have been carried out (Fig. 4b, Table 2).

Forty-nine interrelated terms were determined in cluster 3 (blue). The highest co-occurrence term was recorded for duck (48 co-occurrences) among the 49 terms. The general analysis of the terms in cluster 3 indicated that lead poisoning in wild birds comes to the fore (Fig. 4b, Table 2).

Lead accumulation in various organs of birds affects almost every physiological system and causes serious poisoning and even death if the accumulation exceeds the threshold values. However, in the last 10 years, many studies have been carried out on the effect of lead from ammunition on other wild bird groups, including raptors. Studies revealed that raptors and vultures accumulated the lead metal originated from the rifle ammunition in offal or carcasses of the killed hunting animals.

The most studied bird species in this cluster are *Anas platyrhynchos* (mallard) and *Cygnus olor* (mute swan). The highest number of studies related to this subject has been carried out in the USA (Fig. 4b, Table 2).

Thirty-eight interrelated terms were identified in cluster 4 (yellow). The most frequent term used in cluster 4 was selenium (106 co-occurrences) metal. The effects of metal pollution in aquatic ecosystems on birds are discussed in this cluster. Aquatic environments are highly vulnerable to exposure to pollutants compared to terrestrial environments. Most of the pollutants reach sea and coastal ecosystems along with river and stream currents and cause metal accumulation. In this cluster, a relationship was established between bird and environment pollution and useful information was obtained on the extent of environmental pollution caused by heavy metals. Common eider (*Somateria mollissima*), herring gull (*Larus argentatus*), and bald eagle (*Haliaeetus leucocephalus*) species were used as indicators in these studies. The highest number of studies on this subject was carried out in the USA (Fig. 4b, Table 2).

Twenty-nine interrelated terms were identified in cluster 5 (purple). The highest number of co-occurrence was recorded for copper (144 co-occurrences) metal in cluster 5. The studies in cluster 5 were focused on determining the heavy metal concentrations accumulated in various tissues (liver, kidney, bone, etc.), feathers, and food of juvenile individuals of heron birds (*Nycticorax nycticorax*, *Ardea cinerea*, *Egretta garzetta*, *Egretta gularis*, *Bubulcus ibis*). The content analysis of the studies showed that copper (Cu), iron (Fe), and zinc (Zn) elements are in high ratios. The elements such as aluminum (Al), manganese (Mn), Cu, Zn, and Fe, which are among the essential metals, are necessary in the life cycle (growth, feather formation, reproduction, etc.) of living organisms. These metals are present in certain amounts in the bodies of living creatures. The most of the studies on this subject have been carried out in South Korea (Fig. 4b, Table 2).

Six interrelated terms were determined in cluster 6 (turquoise). The highest number of co-occurrence was

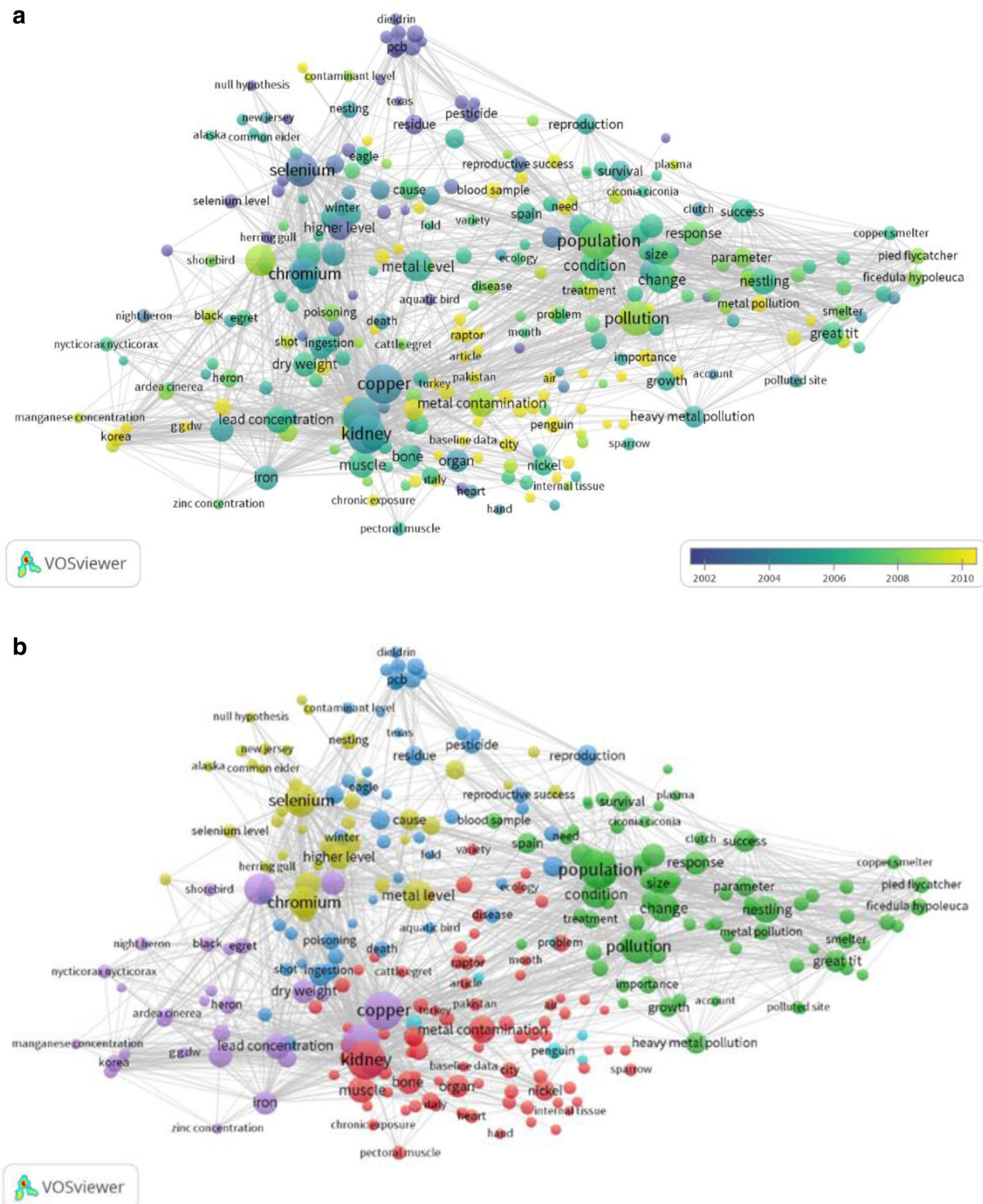

Fig. 4 Trend **a** and term **b** network analysis of documents related to heavy metal and birds (1970 to May 2020). Hereby, the six clusters were identified and visualized with different colors

Table 2 The terms extracted from the 971 documents and clusters corresponding to the terms retrieved from documents

No	Terms	Cluster	Occurrences	R. Sc.	No	Terms	**Cluster**	**Occurrences**	**R. Sc.**
1	AAS	1	15	0.9948	42	Month	1	13	0.4094
2	Age class	1	13	0.2956	43	Muscle	1	71	0.7721
3	Air	1	15	0.5518	44	Netherlands	1	11	0.3658
4	Anthropogenic activity	1	17	0.5464	45	Nickel	1	40	0.4164
5	Baseline data	1	12	0.6788	46	November	1	12	0.5283
6	Biomagnification	1	11	0.7631	47	Organ	1	52	0.6193
7	Bird feather	1	15	0.6267	48	Pakistan	1	16	1.0328
8	Bone	1	57	0.4566	49	Pectoral muscle	1	19	0.9207
9	Brain	1	28	0.7048	50	Pigeon	1	16	0.5989
10	Breast feather	1	23	0.7648	51	Plasma mass spectrometry	1	19	0.9227
11	*Buteo buteo*	1	12	1.021	52	Potential risk	1	11	0.5717
12	Cattle egret	1	14	1.0366	53	Problem	1	28	0.399
13	Cd concentration	1	38	0.5156	54	Raptor	1	21	0.4748
14	Cd level	1	19	0.7697	55	Review	1	16	0.511
15	Chemical	1	26	0.4021	56	Rural area	1	12	0.6114
16	Cormorant	1	19	0.7919	57	Significant correlation	1	24	0.5163
17	Determination	1	19	0.635	58	Significant positive correlation	1	13	0.6763
18	Ecology	1	17	0.4131	59	Soft tissue	1	11	0.5008
19	Egg content	1	22	0.3755	60	Sparrow	1	17	0.6641
20	Example	1	13	0.5172	61	Specimen	1	28	0.6102
21	Fact	1	15	0.5017	62	Total	1	21	0.4264
22	Family	1	14	0.6736	63	Toxic heavy metal	1	10	0.7874
23	Gender	1	24	0.5314	64	Trace metal concentration	1	12	0.5733
24	Heart	1	20	0.7708	65	Turkey	1	12	0.6253
25	Heavy metal accumulation	1	15	0.5039	66	Urban area	1	12	0.7284
26	Heavy metal content	1	21	0.6385	67	Variety	1	14	0.4424
27	House sparrow	1	10	0.9869	68	Wetland	1	42	0.4424
28	Human activity	1	13	0.5805	69	Zn concentration	1	13	0.7244
29	Internal tissue	1	10	0.6971	70	ICP MS	1	20	0.9844
30	İntestine	1	11	0.9121	71	India	1	13	0.6572
31	Japan	1	11	0.9353	72	Iran	1	16	0.7272
32	Kidney	1	141	0.5306	73	Italy	1	18	0.6654
33	Life	1	15	0.3925	74	Influence	1	10	0.4411
34	Liver sample	1	13	0.7776	75	Account	2	13	1.1406
35	Lowest concentration	1	11	0.5656	76	Biomarker	2	23	0.4323
36	Lung	1	21	0.9014	77	Black kite	2	10	1.7744
37	Malaysia	1	11	1.7238	78	Blood sample	2	26	0.4335
38	Mean level	1	13	0.7653	79	Blue tit	2	10	1.9741
39	Metal accumulation	1	20	0.5842	80	Body mass	2	18	0.3499
40	Metal contamination	1	69	0.2228	81	Breeding	2	19	1.0313
41	Metallothionein	1	20	0.5718	82	Calcium	2	17	0.8539
83	Change	2	80	0.5434	124	Pied flycatcher	2	27	3.5375
84	*Ciconia ciconia*	2	14	1.1939	125	Plasma	2	12	0.8952
85	Clutch	2	19	0.9218	126	Polluted area	2	24	2.6535
87	Clutch size	2	19	1.9569	127	Pollution	2	115	0.3913
88	Condition	2	76	0.2898	128	Pollution gradient	2	27	3.0163
89	Control	2	25	0.5531	129	Pollution source	2	18	3.1766
90	Control group	2	13	0.717	130	Population	2	137	0.3532
91	Copper smelter	2	19	3.5304	131	Proportion	2	25	0.4409

Table 2 (continued)

No	Terms	Cluster	Occurrences	R. Sc.	No	Terms	**Cluster**	**Occurrences**	**R. Sc.**
92	Decrease	2	21	0.4689	132	Reduction	2	18	0.7557
93	Density	2	28	0.7367	133	Relation	2	33	0.4454
94	Development	2	48	0.2701	134	Response	2	54	0.9615
95	Distance	2	24	0.8428	135	Shell	2	18	1.0649
96	Eggshell thickness	2	10	1.0786	136	Size	2	38	0.688
97	Emission	2	25	1.2638	137	Smelter	2	31	2.3037
98	Environmental pollution	2	27	0.7296	138	Spain	2	41	0.4966
99	Excrement	2	12	0.7013	139	Spring	2	11	0.2248
100	Feces	2	20	0.706	140	Success	2	48	1.221
101	*Ficedula hypoleuca*	2	28	3.3877	141	Survival	2	42	0.6099
102	Fledgling	2	20	0.4632	142	Treatment	2	28	0.6685
103	Great Tit	2	50	2.2004	143	Unpolluted area	2	10	0.9472
104	Growth	2	37	0.4007	144	Vicinity	2	14	2.4993
105	Heavy metal exposure	2	15	1.3292	145	White stork	2	12	1.4808
106	Heavy metal pollution	2	45	0.7645	146	Reference site	2	25	0.2668
107	Importance	2	31	0.4998	147	Polluted environment	2	12	2.0079
108	Increase	2	42	0.3134	148	*Anas platyrhynchos*	3	20	1.2851
109	Interaction	2	21	0.394	149	Aquatic bird	3	15	0.3781
110	Metal exposure	2	21	0.9302	150	Aquatic ecosystem	3	13	0.4677
111	Metal pollution	2	27	1.1056	151	Average	3	22	0.5531
112	*Milvus migrans*	2	10	1.8936	152	Biphenyl	3	12	2.2586
113	Negative effect	2	21	0.4288	153	Carcass	3	20	0.7359
114	Nest	2	37	0.6233	154	Combination	3	15	0.6304
115	Nestling	2	68	1.1915	155	Contaminant concentration	3	13	0.6269
116	Oxidative stress	2	11	0.825	156	Contaminant level	3	14	1.0839
117	Parameter	2	38	1.233	157	Dde	3	24	2.4941
118	Parent	2	12	1.0608	158	Ddt	3	20	2.5259
119	Parus	2	15	2.5581	159	Death	3	27	0.6182
120	Passerine	2	24	1.5512	160	Decade	3	18	0.5157
121	Passerine bird	2	19	2.1177	161	Detection limit	3	12	0.883
122	Performance	2	21	2.5527	162	Dieldrin	3	15	2.4781
123	Period	2	55	0.5348	163	Disease	3	22	0.6532
164	Duck	3	48	0.5683	203	Coastal area	4	10	0.5234
165	Eagle	3	31	1.0397	204	Common eider	4	13	1.584
166	Eggs	3	19	1.2489	205	Decline	4	36	0.5112
167	Fold	3	10	0.6285	206	Eider	4	14	1.5353
168	Gizzard	3	12	1.2161	207	Environmental pollutant	4	14	0.4836
169	Hcb	3	10	2.8133	208	Feed	4	19	0.6252
170	Heavy metal residue	3	14	1.9547	209	Gull	4	62	0.5537
171	Ingestion	3	29	0.8945	210	*Haliaeetus leucocephalus*	4	12	2.0388
172	Lead exposure	3	18	0.5679	211	Herring gull	4	15	1.3974
173	Lead poisoning	3	20	1.3315	212	Higher level	4	54	0.8031
174	Lead shot	3	17	1.1225	213	Highest level	4	40	0.9874
175	Loss	3	22	0.5491	214	İsland	4	18	1.0866
176	Low concentration	3	10	0.5856	215	*Larus argentatus*	4	15	1.1819
177	Mallard	3	29	1.0174	216	Levels	4	47	0.6346
178	Mortality	3	43	0.4169	217	Lower level	4	17	1.2955
179	Mute swan	3	10	0.5541	218	Lowest level	4	13	2.0996
180	Organochlorine	3	28	1.8929	219	Magnitude	4	12	0.9241

Table 2 (continued)

No	Terms	Cluster	Occurrences	R. Sc.	No	Terms	Cluster	Occurrences	R. Sc.
181	PCH	3	35	4.4593	220	Manganese	4	15	1.4661
182	PCBS	3	29	2.1306	221	Marine bird	4	10	0.9071
1183	Pesticide	3	34	1.0342	222	Marine environment	4	22	0.4696
184	Poisoning	3	31	0.8233	223	Mercury level	4	44	0.6554
185	Polychlorinated biphenyl	3	18	1.9956	224	Metal level	4	89	0.4527
186	Ppm	3	38	0.5354	225	Nesting	4	30	0.9169
187	Release	3	15	0.4468	226	New Jersey	4	15	1.3242
188	Reproduction	3	41	0.6738	227	Predator	4	26	0.5818
189	Reproductive success	3	27	0.306	228	Selenium	4	106	0.8341
190	Residue	3	37	1.115	229	Selenium level	4	21	1.3907
191	Selenium concentration	3	20	0.7364	230	*Somateria mollissima*	4	12	1.7769
192	Shot	3	20	1.1468	231	Temporal trend	4	10	0.5095
193	Texas	3	10	1.5006	232	Total mercury	4	14	0.6633
194	Waterfowl	3	26	0.4999	233	USA	4	23	0.6902
195	Wet weight	3	32	0.7056	234	Young bird	4	11	1.1517
196	Winter	3	27	0.3841	235	*Ardea cinerea*	5	11	2.5235
197	Abundance	4	20	0.5945	236	Background level	5	27	1.6229
198	Alaska	4	13	1.9164	237	Black	5	23	1.0952
199	Bald eagle	4	13	1.9817	238	Cadmium concentration	5	55	1.4025
200	Cadmium level	4	27	0.5443	239	Chick	5	55	0.4334
201	Cause	4	42	0.4446	240	Copper	5	144	0.33
202	Chromium	4	97	0.8411	241	Copper concentration	5	19	2.2674
242	Dry weight	5	56	0.5892	256	Shorebird species	5	10	2.1367
243	Egret	5	27	1.1308	257	G G Dw	5	13	1.9884
244	*Egretta garzetta*	5	16	1.3292	258	Toxic level	5	14	0.8006
245	Essential element	5	36	0.9373	259	Trace element concentration	5	22	0.4498
246	Gray heron	5	11	2.3268	260	Wild bird	5	30	1.5306
247	Heavy metal concentration	5	60	0.3625	261	Zinc	5	135	0.4205
248	Heron	5	30	1.3156	262	Zinc concentration	5	13	1.7359
249	Iron	5	55	1.0159	263	Iron	5	15	2.6131
250	Korea	5	29	2.477	264	Aluminum	6	12	0.4512
251	Lead concentration	5	63	0.8526	265	Antarctica	6	12	1.982
252	Manganese concentration	5	11	2.8591	266	Cobalt	6	25	0.7039
253	Night heron	5	19	1.9128	267	Excreta	6	12	1.0485
254	*Nycticorax nycticorax*	5	19	1.9852	268	Penguin	6	27	1.1023
255	Shorebird	5	18	0.8449	269	Point	6	23	0.4024

R.Sc. relevance score, represent specific topics covered by the text data; cluster, items may be grouped into clusters. A cluster is a set of items included in a map; occurrences, the number of documents in which a keyword occurs

recorded for penguin (27 co-occurrences) in cluster 6. Heavy metal levels were investigated in the feces and feathers of penguins. Cobalt (Co) was the most prominent metal contaminant (Fig. 4b, Table 2).

Geographical distribution of the documents

The minimum number of documents for a country was accepted as 24 to determine the global distribution of published documents. Thirteen of 37 countries met this threshold. The total strength of author connectivity with other countries was calculated for each of the 13 countries. Countries with the high total connectivity were selected. Overall, the USA leads the list with 240 publications (24.72%) in global publication share of the 13 countries, followed by Spain (79; 8.13%), Canada (59; 6.07%), China (56; 5.77%), and the UK (47; 4.84%) (Tables 3 and Supplementary Table 1). Four clusters were identified for the citations. Fourteen countries including

Table 3 Top 13 countries according to the highest number of published documents related with heavy metal accumulation in birds

Country	Doc.	%	TGCS	TGCS/ Doc.	TLS (citation)	TLS (co-authorship)	Particle pollution (μg/m^3)*
USA	240	24.71	7806	32.52	1448	60	9.05
Spain	79	8.13	2382	30.15	789	67	10.34
Canada	59	6.07	3596	60.95	613	32	7.91
China	56	5.76	989	17.66	426	25	41.17
UK	47	4.84	3097	65.90	583	48	10.83
Finland	44	4.53	1321	30.02	565	35	6.57
Poland	42	4.32	751	17.88	416	9	22.39
Belgium	33	3.40	1646	49.87	684	21	13.52
Italy	32	3.29	1056	33.00	455	14	14.95
Japan	28	2.88	1023	36.53	360	15	12.00
South Korea	28	2.88	401	14.32	445	2	24.01
Norway	27	2.78	1207	44.70	243	39	7.61
Germany	24	2.47	646	26.91	267	45	13.01

TGCS (total global citation score) = total number of citations received; Doc, documents; citation/article, TGCS/number of articles published by each country; %, total number of articles in each country × 100/total number of articles; TLS, total link strength: indicates the total strength of the co-authorship links of a given researcher with other researchers,* Those values were retrieved from the World Population Review (World most polluted countries 2018 (average: 10 μg/m^3 : 2.5 ppm). (World Air Quality Report 2019)

Argentina, Australia, Brazil, Canada, Chile, Denmark, France, Germany, Japan, Mexico, New Zealand, Norway, South Africa, and England are placed in cluster 1 (red). Cluster 2 (green) include 11 countries which are the China, Hong Kong, India, Iran, Italy, Malaysia, Nigeria, Pakistan, South Korea, Turkey, and the USA. Cluster 3 (blue) includes 10 countries which are Austria, Belgium, Czech Republic, Finland, Hungary, Netherlands, Portugal, Russia, Spain, and Sweden, while cluster 4 (yellow) includes Colombia and Poland (Fig. 5a).

In addition, eight clusters were identified related to co-authorship (Fig. 5b). Six countries in cluster 1 (red) (Belgium, Finland, Hungary, Netherlands, Portugal, and Spain); five countries in cluster 2 (green) (Brazil, Chile, Colombia, France, and Mexico); five countries in cluster 3 (blue) (China, Hong Kong, Italy, Norway, and Pakistan); five countries in cluster 4 (yellow) (Austria, Denmark, Germany, Poland, and Sweden); four countries in cluster 5 (purple) (Australia, Canada, New Zealand, and the UK); four countries in cluster 6 (Japan, Nigeria, South Africa, and South Korea); four countries in cluster 7 (orange) (Argentina, Iran, USA, and Turkey); and two countries in cluster 8 (brown) (India and Russia) were identified.

According to the correlation matrix, positive and significant correlations were noted for TGCS and document number ($r = 0.925$; $p < 0.01$), document number and TLS (citation) ($r = 0.929$; $p < 0.01$), TGCS and TLS (citation) ($r = 0.912$; $p < 0.01$) as well as TGCS and TLS (co-author) ($r = 0.612$; $p < 0.05$). However, significant but negative correlation was observed between TGCS/document number and participle pollution ($r = -0.590$; $p < 0.05$). Interestingly, even though all correlations were not significant, negative correlation coefficients were found between particle pollution and other variables (Supplementary Fig. 1).

The results were also visualized using principal component analysis, being discriminated on the correlations between the variable (Fig. 6). Furthermore, publication origins (countries) were also well-defined and clearly discriminated with respect to the variables.

The results for the percentage of total citations for the total number of documents by the countries indicated that England ranks at the top with a total of 3097 (65.90%) citations received to 47 documents. The number of published documents in the USA and Spain is higher than other 11 countries; however, these two countries are placed towards the ends among the first 13 countries in the percentage of the total number of citations received to the total document (Fig. 6).

Co-authorship mapping and clustering

The main parameters for scientific collaboration between authors are mapping and clustering (Yu 2015; Tabatabaei-Malazy et al. 2016). The minimum number of scientific papers published by an author was accepted as 5 documents to obtain the co-authorship network map. Sixty-nine authors out of 2511 authors who conducted scientific studies on this subject met this threshold. The total strength of co-authorship connection with other authors was calculated for each of the 69 authors. The authors with the highest total link strength were selected. Seven of the authors were excluded from the analysis

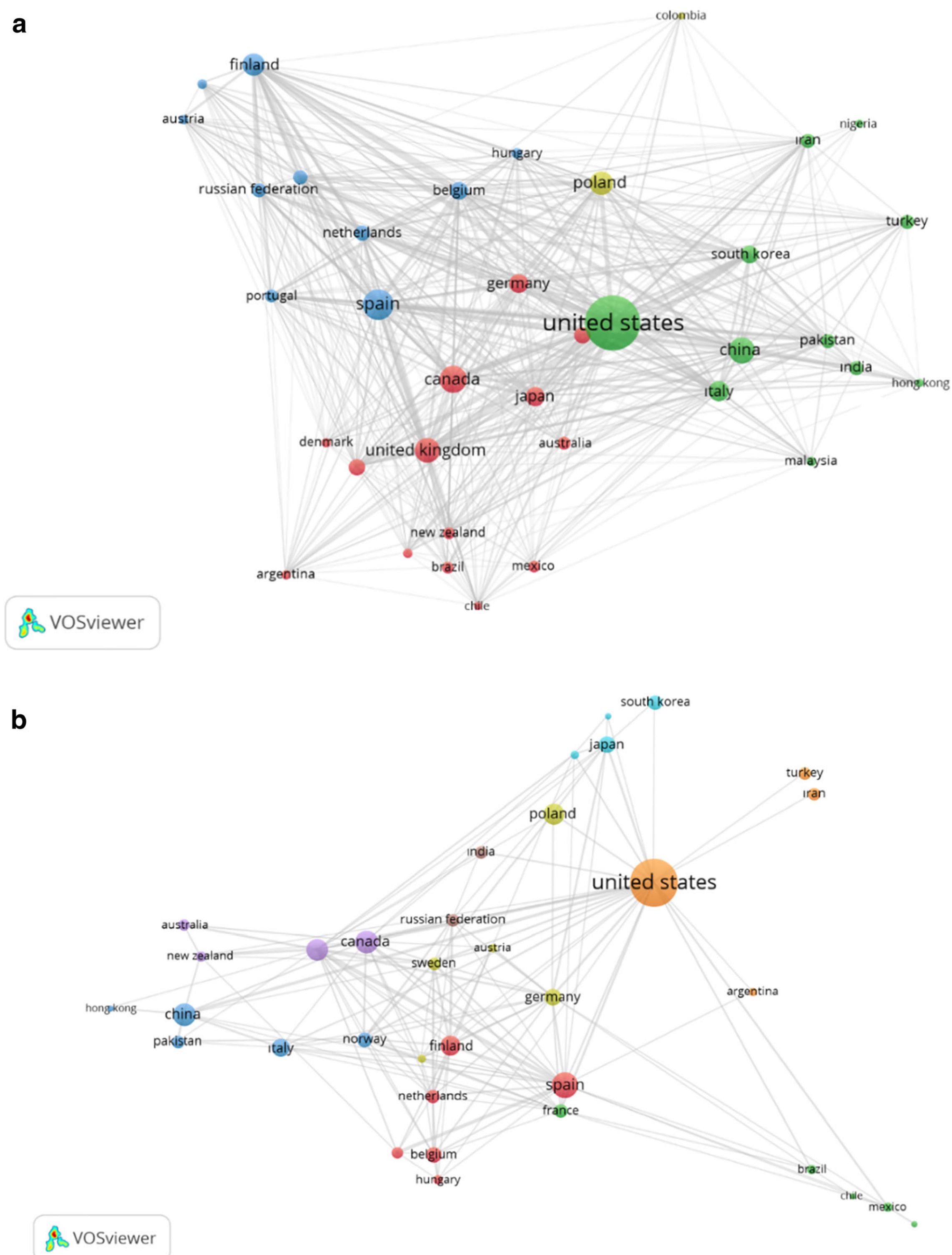

Fig. 5 **a** Citation network of countries that have published at least 5 documents on the relationship between heavy metal pollution and birds between 1970 and May 2020. **b** The co-authorship network of countries that have published at least 5 documents on heavy metal contamination—the relationship between birds between 1970 and May 2020

because they had no co-authorship connection. The co-authorship network is shown in Fig. 7. The five authors with the highest number of publications were "Burger J. (66 publications)," "Gochfeld M. (47 publications)," "Eeva T. (35 publications)," "Eens M. (25 publications)," and "Kim J. (22 publications)." The number of documents belonging to other authors is given in detail in Table 4.

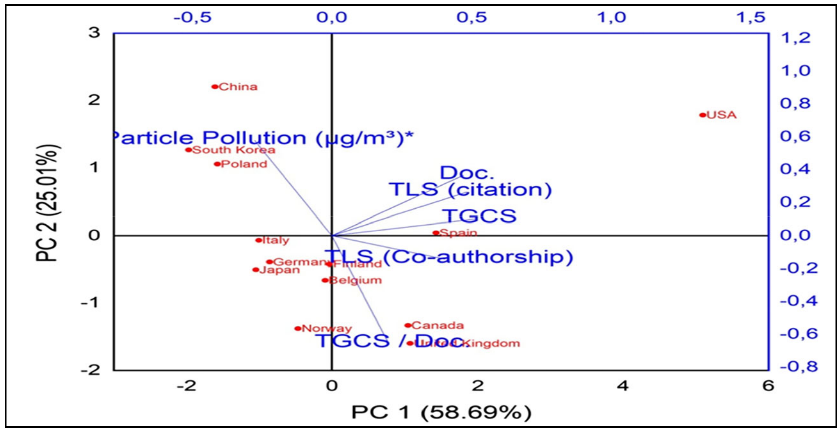

Fig. 6 Principal component analysis of the variables to reduce the dimension of the parameters and to sort the groups with variables

Top productive institutes published documents

To determine the most popular organizations, minimum number of organizations was set to be 3. The citation numbers were ignored. Of the 2309 organizations, 34 meet the threshold. For each of the 34 organizations, the total strength of the co-authorship link with other organizations was calculated. The organizations with the greatest total link strength were selected. Of the selected 34 organizations, the USA was dominant with 5 departments or institutions. "Environmental and Occupational Health Sciences Institute, Piscataway, New Jersey, USA" has stood its first place with 28 publications (2.88%) (Table 6). Twenty-five clusters were identified. Cluster 1 had three items including "Division of Life Sciences, Rutgers University, Allison Road, Piscataway, New Jersey, USA," "Environmental and Occupational Health Sciences Institute, Piscataway, New Jersey, USA," and "Environmental and Community Medicine, Umdnj-Robert Wood Johnson Medicine School, Piscataway, New Jersey, USA."

The second cluster included two items which were "State School of Higher Education in Chełm, Pocztowa, Chełm, Poland" and "Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna, Lublin, Poland" (Table 5). The rest institutes were included into different clusters, meaning that none of them are connected to each other (Fig. 8).

Contributions by keyword

Retrieval and identification of the commonly proposed keywords provide raw information with respect to the research topics and hence the keywords are considered representative content of the document (Kulak 2018).

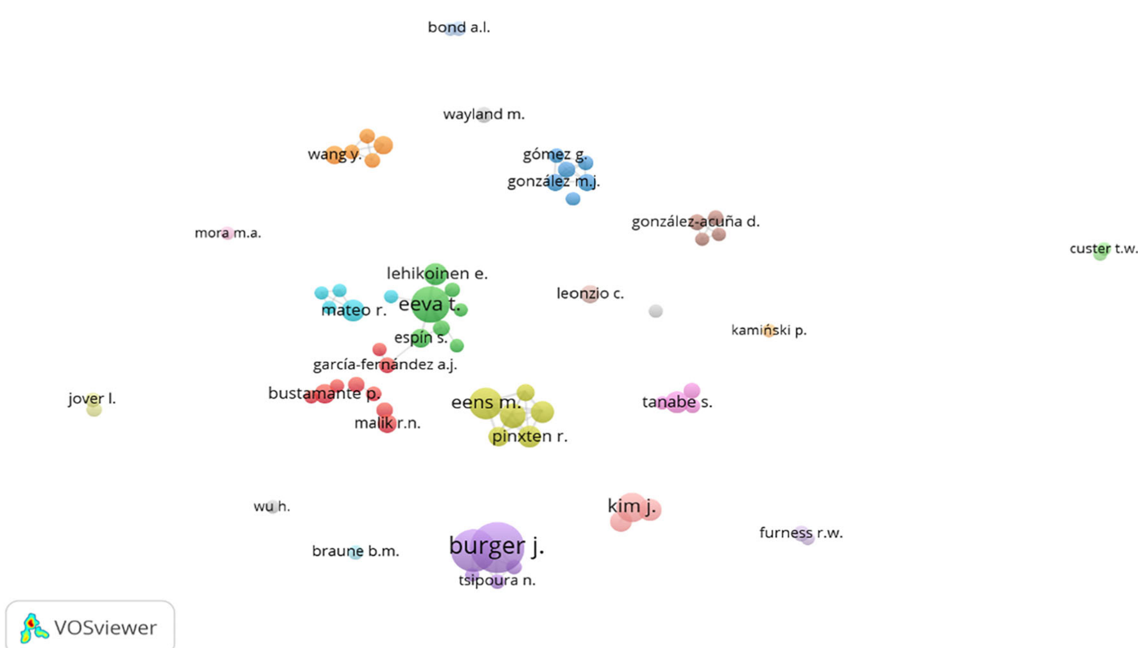

Fig. 7 Heavy metal pollution—map of co-authoring network of published documents on birds

Table 4 Top authors according to the highest number of published documents concerned with the current topic of the study

Author	Country	Affiliation	h-i	Doc.	%	Cit.	CA	TLS
Burger J.	USA	Environmental and Occupational Health Sciences Institute and Consortium for Risk Evaluation with Stakeholder Participation, Piscataway, NJ, USA	62	66	6.80	2486	37.70	63
Gochfeld M.	USA	Environmental and Occupational Health Sciences Institute and Consortium for Risk Evaluation with Stakeholder Participation, Piscataway, NJ. USA	49	47	4.84	1875	39.90	61
Eens M.	Belgium	Department of Biology, University of Antwerp (UIA), Universiteitsplein 1, 2610 Wilrijk, Belgium	55	25	2.57	1379	55.16	65
Eeva T.	Finland	Section of Ecology, University of Turku, FIN-20014 Turku, Finland	33	35	3.60	1123	32.08	46
Kim J.	S. Korea	Kyung Hee University, Seoul, South Korea	13	22	2.27	315	14.31	23
Dauwe T.	Belgium	Department of Biology, University of Antwerp (UIA), Universiteitsplein 1, 2610 Wilrijk, Belgium	31	16	1.64	1080	67.50	50
Bervoets l.	Belgium	Department of Biology, University of Antwerp, Campus Middelheim, Antwerp, Belgium	46	13	1.33	893	68.70	41
Pinxten R.	Belgium	Department of Biology, University of Antwerp (UIA), Universiteitsplein 1, 2610 Wilrijk, Belgium	40	12	1.23	746	62.17	34
Tanabe S.	Japan	Center for Marine Environmental Studies, Ehime University, Tarumi 3–5-7, Matsuyama 790–8566, Japan	86	12	1.23	690	57.50	11
Lehikoinen E.	Finland	Section of Ecology, University of Turku, FIN-20014 Turku, Finland	31	12	1.23	597	49.75	14
Mateo R.	Spain	Institute for Game and Wildlife Research, IREC, Ciudad Real, Spain	38	12	1.23	396	33.00	18
Oh J.-M.	S. Korea	Kyung Hee University, Seoul, South Korea	13	12	1.23	105	8.75	13

CA**,** Cit./Doc.; h-i**.,** h-index; Doc, documents; %, total number of articles in each author × 100/total number of articles; TLS (total link strength) indicates the total strength of the co-authorship links of a given researcher with other researchers

He (1999) stated that the keyword analysis can exhibit the development and progress of the research frontiers regarding with a knowledge. In the study, a keyword analysis gap has been proposed in documents on the relationship between heavy metal accumulation and birds. This approach can be regarded as the most important contribution to the study. Co-occurrences of keywords can be considered an important factor providing useful information on the relationship between heavy metal accumulation and birds. In this context, the minimum repeating number of a keyword was considered 5 keywords. Ninety-two keywords out of 1552 keywords met this threshold (Table 6).

The combined strength of the arising links along with other keywords was calculated for each of the 92 keywords. Keywords with the highest total link capacity were selected. Accordingly, 8 clusters were identified, but 4 clusters were created based on the keywords: (i) tissue and organ ("Feathers (49 occurrences)"), ("Liver (26 occurrences)"), ("Eggs (19 occurrences)"), ("Blood (15 occurrences)"), ("Egg shells (8 occurrences)"), ("Kidney (5 occurrences)"); (ii) bird species ("*Ficedula hypoleuca* (9 occurrences)"), ("*Parus major* (11 occurrences)"), ("*Haliaeetus leucocephalus* (6 occurrences)"), ("*Anas platyrhynchos* (5 occurrences)"), ("*Ciconia ciconia* (5 occurrences)"), ("*Bubulcus ibis* (5 occurrences)"); (iii) adverse effects of metal pollution ("Reproduction (14 occurrences)"), ("Breeding success (11 occurrences)"), ("Oxidative stress (8 occurrences)"), ("Lead poisoning (8 occurrences)"), ("Mortality (6 occurrences)"); and (iv) heavy metals ("Lead (74 occurrences)"), ("Mercury (69 occurrences)"), ("Cadmium (50 occurrences)"), ("Chromium (19 occurrences)"), ("Selenium (23 occurrences)"), ("Manganese (14 occurrences)"), ("Zinc (13 occurrences)"), ("Copper (13 occurrences)"). Keyword formation analysis and clustering methods are useful methods used to obtain a more accurate view of the study areas (Kulak et al. 2019).

Therefore, the results indicate the capacity of keywords to find the documents analyzed. An example for visualization of the clusters created using the VOSviewer was shown in Fig. 9.

Major journals publishing documents on the effects of heavy metal pollution and accumulation on birds

The characteristics of the main journals publishing documents on the effects of heavy metal pollution or accumulation on birds are shown in Table 8. The "Science of the Total Environment" has scored the first rank with 92 documents, followed by "Archives of Environmental Contamination and Toxicology" (89 documents), "Environmental Monitoring and Assessment" (56 documents), and "Environmental Pollution" (56 documents). The impact factor of the journals was remarkably different from each other. The trends in

Table 5 The most productive organizations in publishing the studies concerned with heavy metal accumulation and birds (organizations publishing at least 3 documents are included)

Organization	Countries	Doc.	%	TGCS	TGCS/ Doc.	TLS
Environmental and Occupational Health Sciences Institute, Piscataway, New Jersey	USA	28	2.88	991	35.39	11
Department of Biology, University of Turku, Turku	Finland	19	1.95	504	26.52	0
Environmental and Community Medicine, Umdnj-Robert Wood Johnson Medicine School, Piscataway, New Jersey	USA	19	1.95	711	37.42	7
Division of Life Sciences, Rutgers University, Allison Road, Piscataway, New Jersey	USA	13	1.33	330	25.38	11
Department of Biological Sciences, Rutgers University, Piscataway, New Jersey	USA	7	0.72	299	42.71	10
Department of Biology, University of Antwerp (U.I.A.), Universiteitsplein, Wilrijk	Belgium	7	0.72	455	65.00	0
Department of Environmental Science and Engineering, Kyung Hee University, Yongin, Gyeonggi	South Korea	7	0.72	127	18.14	0
Center for Marine Environmental Studies (CMES), Ehime University, Bunkyo-Cho, Matsuyama	Japan	5	0.51	106	21.20	0
Department of Veterinary Sciences, University of Trás-Os-Montes e Alto Douro, Quinta Dos Prados, Vila Real	Portugal	3	0.30	33	11.00	0
Department of Environment Conservation, Ehime University, Tarumi, Matsuyama	Japan	3	0.30	214	71.33	0
Gansu Key Laboratory of Biomonitoring and Bioremediation for Environmental Pollution, School of Life Sciences, Lanzhou University, Lanzhou	China	3	0.30	2	0.66	0
Mendel University of Agriculture and Forestry, Zemědělská, Brno	Czech Rep.	3	0.30	35	11.66	0
National Water Research Institute, Environment Canada, Burlington	Canada	3	0.30	463	154.33	0
Patuxent Wildlife Research Center, U.S. Fish and Wildlife Service, Laurel, Maryland	USA	6	0.61	102	17.00	0
State School of Higher Education in Chełm, Pocztowa, Chełm	Poland	3	0.30	7	2.33	3
Young Researchers Club, Kermanshah Branch, Islamic Azad University, Kermanshah	Iran	3	0.30	50	16.66	0
Inst. de Invest. en Recurs. Cineget., Ronda de Toledo, Ciudad Real	Spain	3	0.30	64	21.33	0
Institute for Marine and Antarctic Studies, 20 Castray Esplanade, Tasmania	Australia	3	0.30	59	19.66	0
Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna, Lublin	Poland	3	0.30	7	2.33	3

TGCS (total global citation score) = total number of citations received; Doc, documents

Citation/article, TGCS/number of articles published by each country; TLS (total link strength), indicates the total strength of the co-authorship links of a given researcher with other researchers

publishing regarding with journal impact factors were not steady. Details of the findings are shown in Table 7.

The source network map of journals including the original and review articles on heavy metal accumulation in birds also contains the journals published between 1970 and May 2020 with at least 30 common citations (Fig. 10 and Fig. 11).

Some studies on heavy metal accumulation in various tissues and organs of birds

Birds are globally accepted bioindicator organisms for monitoring environmental inorganic elements. The raptors are the most frequently studied living organisms (Carneiro et al. 2015; Dietz et al. 2006; Espín et al. 2016; Garcıa-Fernandez et al. 2008;). The raptors are exposed to more pollutants due to their location on the top of the food chain and hunting in large geographic areas (Des Granges et al. 1998).

Heavy metal accumulations in the internal organs (liver, heart, kidney, etc.) and feathers of birds have been reported in many studies. The analysis of relevant studies indicated that heavy metal levels in feathers of birds have been investigated in many studies (e.g., Abdullah et al. 2015; Altmeyer et al. 1991; Barbieri et al. 2010; Battaglia et al. 2005; Burger et al. 1993; Dauwe et al. 2003; Durmus et al. 2018; Grúz et al. 2019; Lambertucci et al. 2011; Liu et al. 2020; Mukhtar et al. 2020; Nergiz and Samat 2019; Yamac et al. 2019).

Bird feathers have been frequently used in the studies because feathers accumulate some of the metals more than other body organs, e.g., Hg and As. The feathers play an important role in the excretion of heavy metals from the body, easily

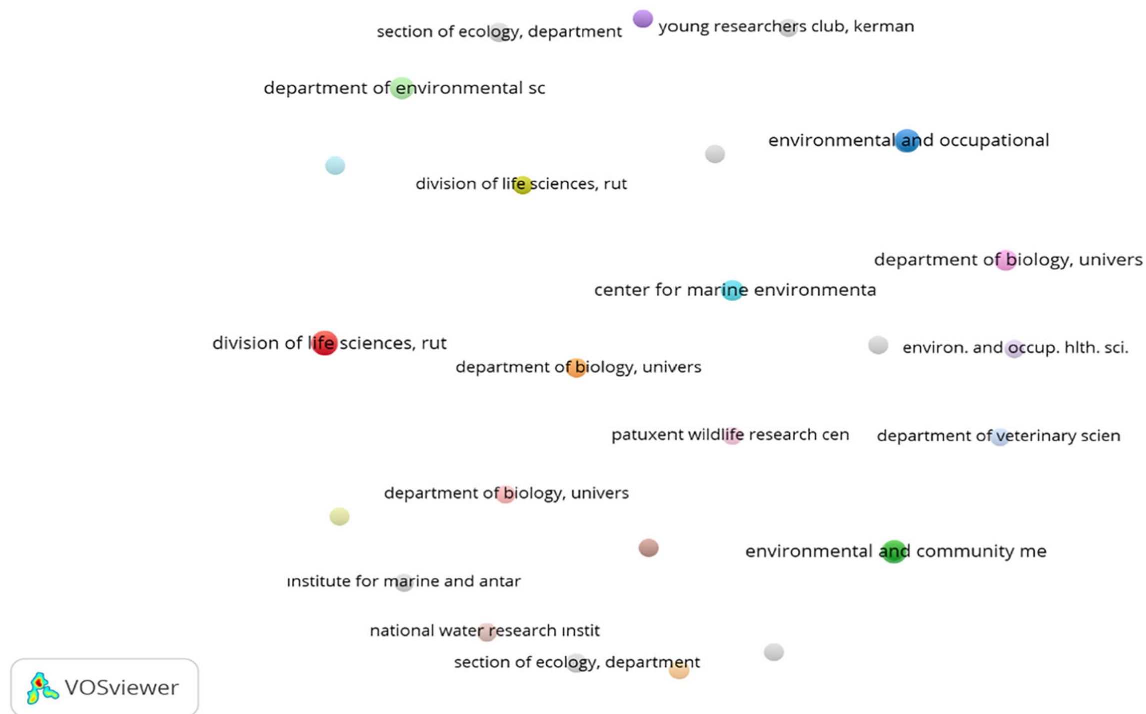

Fig. 8 Map of the co-authorship network of the institutes

sampled (living, dead, or museum specimens), and offer the opportunity to study the endangered creatures.

Information from some studies conducted to determine heavy metal accumulation in birds are presented in Table 8.

Most cited studies on the relationship between heavy metal accumulation and birds

The most cited studies on the heavy metal-bird relationship published between 1970 and May 2020 were listed in Table 9. All the documents belonged to the original studies. The most cited documents are generally the reviews and conference proceedings (see reviews, Scheuhammer 1987; conference proceeding, Furness and Camphuysen 1997).

A high number of citations in review papers are attributed to frequent citations of original articles in the introduction (Koo 2017). The most cited research is a review article, which contains information on the long-term effects of heavy metals on birds. The toxicity of chronic metal exposure of bird food was discussed in the study (Scheuhammer 1987). The paper also contains information on negative effects of metal accumulation on hatching success of birds. The studies revealed that fledglings in need of care (altricial species) are more sensitive to the toxic effects of metal exposure compared to mature (precocial species) ones. The most cited studies agreed that birds are the useful creatures in monitoring environmental metal pollution.

Effects of heavy metal accumulation on birds

Metals(loids) found in the environment arise from both natural resources and human activities (Stankovic et al. 2014; Martin et al. 2012; Niet al. 2009). Pb, Cd, Cr, Cu, As, and Hg are the most common metal(loid) anthropogenic sources contaminants. Towards the last years, with the increase of the urban population, toxic element concentrations in the biosphere have increased significantly. This increase has had a number of negative effects on wildlife, especially humans. Birds accumulate more metal(loid) in their bodies than other living groups due to their location in the food chain and their long life. Especially waterfowls and raptors are exposed to more metal. The disorders caused by metal(loid) exposure in birds are wide and varied. Pb accumulation is often associated with hunting activities. Shooting with lead ammunition for hobby and hunting purposes lead birds to encounter this toxic pollutant (Pain 1992). Pb inhibits the growth and survival of offspring in birds. Hemolytic anemia is seen in wild birds poisoned with Pb. It decreases the egg production and quality by reducing the amount in the plasma and thus decreases the success of the hatching (Buerger et al. 1986; Janssens et al. 2003; Dauwe et al. 2004). Burger et al. 1992a, 1992b reported that breeding failures were observed in heron birds as a result of the accumulation of pollutants such as lead and cadmium. Furthermore, behavioral disorders have been observed (Burger and Gochfeld 1994; Mateo et al. 2003; Scheuhammer 1987). Long stay of Pb metal in nature indirectly or directly causes it to interfere with the food diet of

Table 6 Keywords extracted from documents and clusters corresponding to the keywords retrieved from the documents

No	Keyword	Cluster	Occ.	TLS	No	Keyword	Cluster	Occ.	TLS
1	Age	1	6	20	35	Passerines	2	9	28
2	Antarctica	1	5	12	36	Pollution	2	42	95
3	Aquatic birds	1	5	6	37	Reproduction	2	14	25
4	Bioaccumulation	1	18	47	38	Tissues	2	6	10
5	Bioindicator	1	18	81	39	Waterbirds	2	7	17
6	Bioindicators	1	9	25	40	White stork	2	5	7
7	Biomagnification	1	6	25	41	Biomonitoring	3	5	11
8	Biomonitoring	1	37	125	42	Bird	3	6	13
9	Environmental pollution	1	9	16	43	Birds	3	51	147
10	Feather	1	14	26	44	Cattle egret	3	5	9
11	Hg	1	6	19	45	Contamination	3	13	23
12	Kidney	1	5	26	46	Eggs	3	19	44
13	Liver	1	26	82	47	Eggshells	3	8	13
14	Marine pollution	1	6	30	48	Essential elements	3	5	12
15	Metal	1	11	45	49	Feathers	3	49	155
16	Metalloid	1	5	25	50	Heavy metal	3	44	54
17	Penguins	1	7	19	51	Reproductive success	3	5	15
18	Raptors	1	9	17	52	Toxicology	3	6	12
19	Seabirds	1	27	97	53	Trace metals	3	7	13
20	Soil	1	5	7	54	Background level	4	5	8
21	Trace elements	1	34	58	55	Ecotoxicology	4	12	33
22	Acidification	2	5	10	56	Heavy metal contamination	4	5	10
23	Air pollution	2	16	35	57	Heavy metals	4	189	318
24	Biomarkers	2	7	12	58	Hunting	4	6	13
25	Body condition	2	7	12	59	Lead poisoning	4	8	13
26	Breeding success	2	11	25	60	Lead shot	4	5	12
27	Calcium	2	5	13	61	Livers	4	6	10
28	Carotenoids	2	5	11	62	Waterfowl	4	11	25
29	*Ficedula hypoleuca*	2	9	23	63	Wetland	4	5	9
30	Great tit	2	5	14	64	Wetlands	4	9	29
31	Heavy metal pollution	2	17	25	65	Cadmium	5	50	207
32	Metal pollution	2	9	19	66	Chromium	5	19	116
33	Oxidative stress	2	8	17	67	Copper	5	11	60
34	*Parus major*	2	11	31	68	Lead	5	74	268
No	Keyword	Cluster	Occ.	TLS	No	Keyword	**Cluster**	**Occ.**	**TLS**
69	Mallard	5	5	15	81	Raptor	6	5	13
70	Manganese	5	14	100	82	Seabird	6	10	30
71	Metallothionein	5	7	13	83	Trace element	6	5	8
72	Mortality	5	6	10	84	Arsenic	7	15	75
73	Pesticides	5	7	9	85	Contaminants	7	19	35
74	Selenium	5	23	112	86	Mercury	7	69	238
75	Zinc	5	13	67	87	Organochlorines	7	6	13
76	Avian	6	5	6	88	Shorebirds	7	6	18
77	Bald eagle	6	5	17	89	Stable isotopes	7	11	26
78	Blood	6	15	31	90	Biomarker	8	5	11
79	Excrement	6	5	16	91	Metals	8	37	106
80	*Haliaeetus leucocephalus*	6	6	18	92	Monitoring	8	6	15

TLS (total link strength), indicates the total strength of the co-authorship links of a given researcher with other researchers; Occ. (occurrences), the number of documents in which a keyword occurs

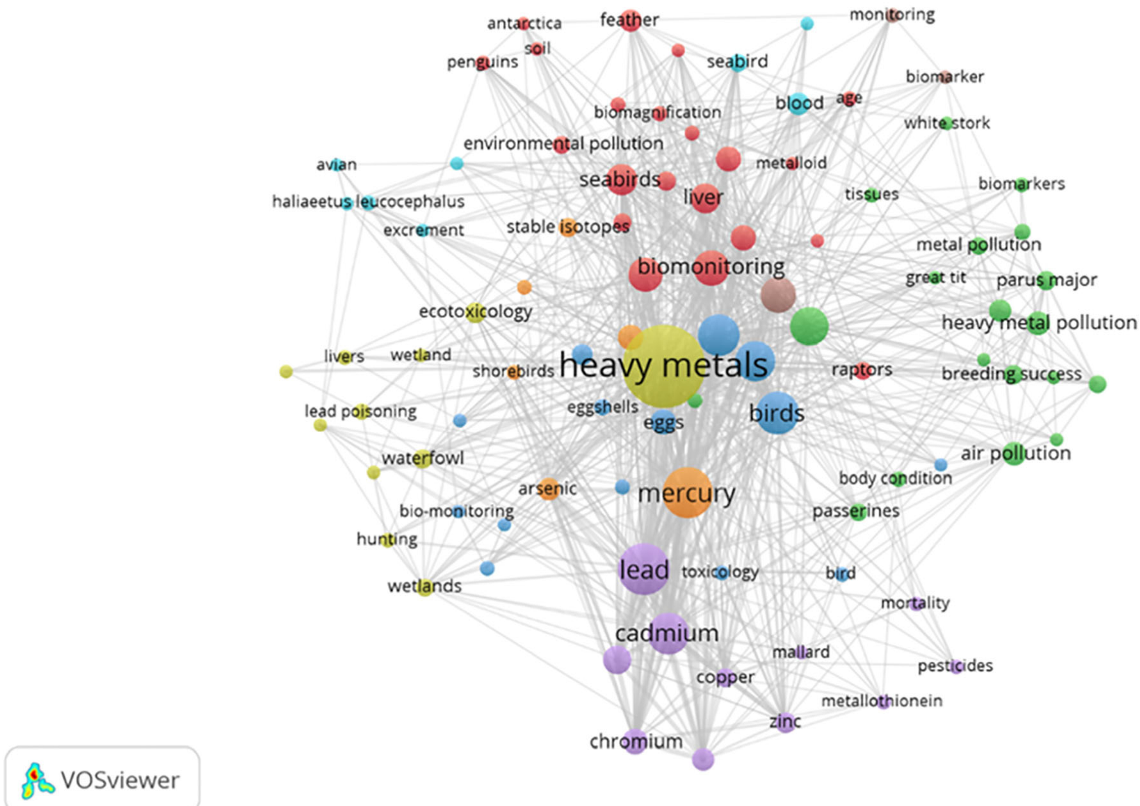

Fig. 9 Visual representation of keywords based on co-occurrences

birds, causing poisoning and death. In countries where lead casting is still in use, the secondary effect of waterfowl hunting is lead poisoning from pellets swallowed by birds feeding on the mud surface (Tavecchia et al. 2001). In addition, shooting and fishing sinkers used for fishing have been reported to cause deaths in seabirds that dive (Sidor et al. 2003). In birds, Cd accumulation leads to kidney and testicular damage, decreased nutrition and slow development, thinning of eggshells, and behavioral disorders (Espejo et al.2018). Hg accumulation has been associated with breeding failure in heron birds (Ochoa-acuña et al. 2002; Scheuhammer et al. 2007). Hg also causes thinning of the eggshell and morbidity; inhibits egg production; and has embryotoxic effects (Heinz and Hoffman 2003; Lundholm 1995). The accumulation of this trace element causes coordination, difficulty in flying and walking, weight loss, paralysis, and death in birds

Table 7 The top and major journals in disseminating the documents relevant in heavy metal accumulation or content in birds

Source	IF	Doc.	%	TGCS	TGCS/ Doc.	TLS
Science of the Total Environment	6.551	92	9,47	4193	45,57	517
Archives of Environmental Contamination and Toxicology	2240	89	9,16	3440	38,65	748
Environmental Monitoring and Assessment	2100	56	5,76	1222	21,82	391
Environmental Pollution	6.792	56	5,76	3727	66,55	497
Bulletin of Environmental Contamination and Toxicology	1.657	44	4,53	767	17,43	180
Ecotoxicology	2.535	36	3,70	1021	28,36	283
Environmental Toxicology and Chemistry	3.410	35	3,60	956	27,31	254
Environmental Science and Pollution Research	3056	29	2,99	164	5,65	253
Ecotoxicology and Environmental Safety	4872	26	2,67	550	21,15	190
Marine Pollution Bulletin	3782	25	2,57	746	29,84	149

TGCS (total global citation score) = total number of citations received; Doc, documents; citation/article, TGCS/ number of articles published by each country; TLS, total link strength; IF, impact factor

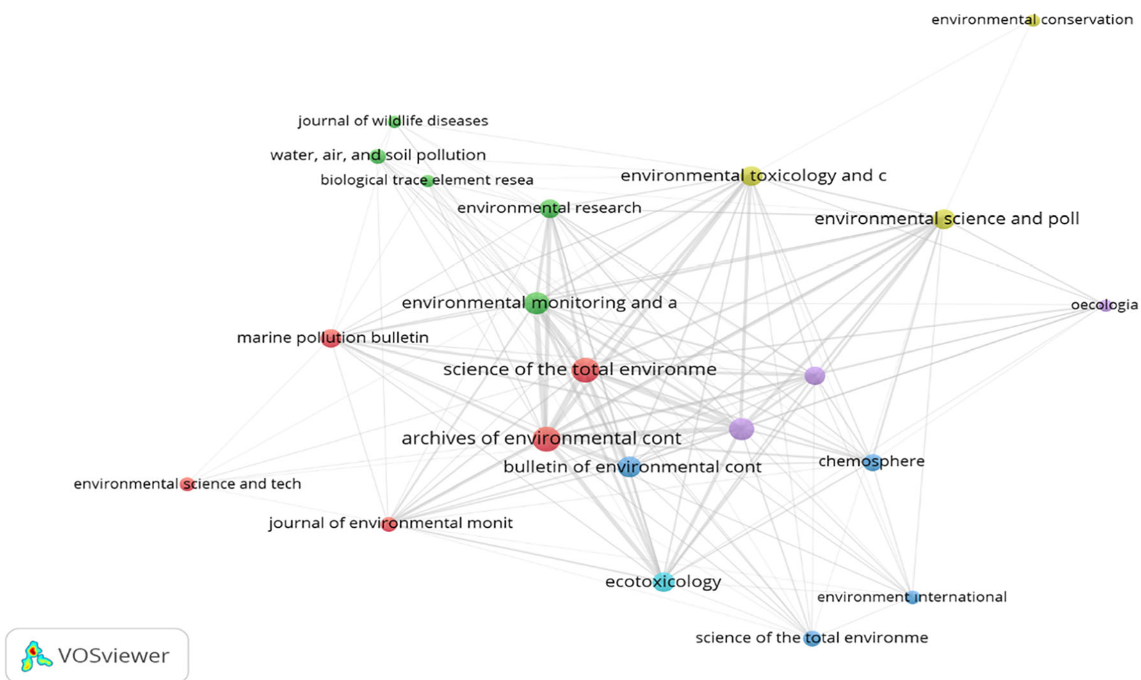

Fig. 10 Citation network of journals that include original and review articles on heavy metal accumulation and birds published between 1970 and May 2020

(Scheuhammer 1987). Arsenic (As) is a metalloid with both metal and nonmetal properties but is often referred to as a metal (or even a heavy metal) (Sánchez-Virosta et al. 2015). Arsenic (As), especially in its inorganic forms, may cause eggshell thinning and increased frequency of egg laying in birds (Chen et al. 2000; Chiou et al. 1997; Hermayer et al. 1977; Stanley et al. 1994; Burger 1994; Koivula et al. 2011). It mostly accumulates in body tissues such as the liver and kidney, causing toxicity to animals above the food chain such as birds of prey (e.g., *Tyto alba*, *Passer domesticus*, *Buteo buteo*, *Accipiter nisus*, *Falco tinnunculus*). Accumulation of metals(loids) in birds causes oxidative stress by increasing

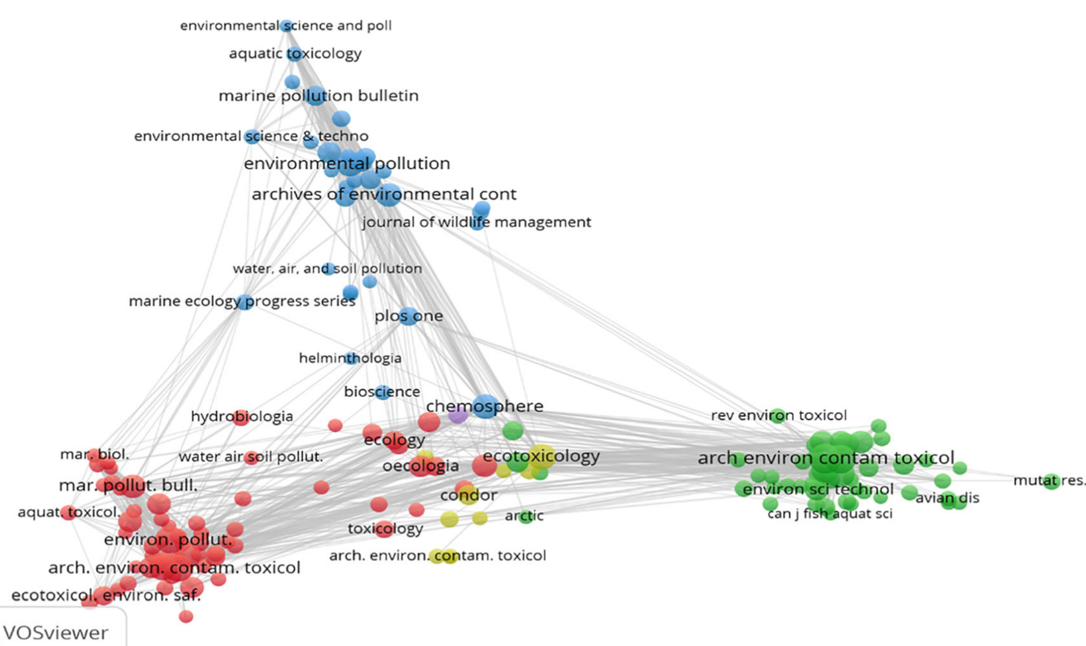

Fig. 11 The citation network, along with the original and review articles on the heavy metal accumulation of the journals, and the journals published between 1970 and May 2020 with at least 30 co-citations were included. Five clusters were identified. In the figure, clusters close to each other show related issues

Table 8 Some heavy metal pollution studies corresponding to metal(loid)s content, accumulated parts, and different taxa of the birds

	Taxon	Categories	Mean or range of means (μg/g)	References		Taxon	Categories	Mean or range of means (μg/g)	References
As	Owl species	Feathers	0.40±0.30	Grúz et al. (2019)	**Cd**	*Gavia arctica*	Liver	5.75	Mochizuki et al. (2013)
	Buzzard	Feathers	0.33±0.17	Grúz et al. (2019)		*Gavia pacifica*	Liver	7.81±0.88	Mochizuki et al. (2013)
	Common kestrel	Feathers	0.29±0.24	Grúz et al. (2019)		*Limosa limosa*	Muscle	0.05±0.007	Lucia et al. (2012)
	Eurasian sparrow-hawk	Feathers	0.32±0.18	Grúz et al. (2019)		Little egret chicks	Liver	10.3±12.8	Kim et al. (2010)
	Aegypius monachus	P. feathers	0.436	Yamaç et al. (2018)		Little egret chicks	Kidney	18.4±26.5	Kim et al. (2010)
	Marus bassanus	Liver	0.916±0.118	Nardiello et al. (2019)		Night-heron chicks	Liver	1.00±1.00	Kim et al. (2010)
	Bubulcus ibis	B. feathers	19–21.4	Ahmadpour et al. (2015)		Night-heron chicks	Kidney	2.20±1.10	Kim et al. (2010)
	Parus major	Tail	31.00	Geens et al. (2010)		*Buteo buteo*	Kidney	12.12±0.590	Battaglia et al. (2005)
	Falconidae	B. feathers	19.61	Nighat et al. (2013)		*Athene noctua*	Kidney	7480±0.230	Battaglia et al. (2005)
	Marus bassanus	Kidney	0.646±0.089	Nardiello et al. (2019)	**Cr**	*Gavia arctica*	Liver	8.15	Mochizuki et al. (2013)
	Marus bassanus	Feathers	0.307±0.024	Nardiello et al. (2019)		*Gavia pacifica*	Liver	6.16±0.64	Mochizuki et al. (2013)
	Limosa limosa	Liver	3.25±2.01	Lucia et al. (2012)		*Limosa limosa*	Liver	0.68±1.82	Lucia et al. (2012)
	Limosa limosa	Muscle	1.97±1.02	Lucia et al. (2012)		*Limosa limosa*	Muscle	0.39±0.35	Lucia et al. (2012)
	Tadorna ferruginea	Kidney	0.019±0.009	Liu et al. (2020)		*Tadorna ferruginea*	Kidney	0.10±0.08	Liu et al. (2020)
Cd	*Limosa limosa*	Liver	0.59±0.77	Lucia et al. (2012)	**Hg**	*Tadorna ferruginea*	Kidney	0.262±0.138	Liu et al. (2020)
	Marus bassanus	Kidney	17.51±3289	Nardiello et al. (2019)		*Limosa limosa*	Muscle	0.40±0.33	Lucia et al. (2012)
	Owl species	Feathers	0.10±0.14	Grúz et al. (2019)		Owl species	Feathers	0.58±0.31	Grúz et al. (2019)
	Buzzard	Feathers	0.09±0.03	Grúz et al. (2019)		Buzzard	Feathers	0.64±0.35	Grúz et al. (2019)
	Common kestrel	Feathers	0.20±0.18	Grúz et al. (2019)		Common kestrel	Feathers	0.59±0.36	Grúz et al. (2019)
	Eurasian sparrow-hawk	Feathers	0.11±0.09	Grúz et al. (2019)		Eurasian sparrow-hawk	Feathers	2.19±1.26	Grúz et al. (2019)
	Aegypius monachus	P. feathers	0.334	Yamaç et al. (2018)		*Marus bassanus*	Liver	7026±0.867	Nardiello et al. (2019)
	Aegypius monachus	Body	0.19	Kavun (2004)		*Marus bassanus*	Kidney	2760±0.465	Nardiello et al. (2019)
	Accipitridae	B. feathers	2.19	Nighat et al. (2013)		*Marus bassanus*	Feathers	4161±0.714	Nardiello et al. (2019)
	Egretta gularis	B. feathers	1.37	Mansouri et al. (2012)		*Limosa limosa*	Liver	1.97±1.69	Lucia et al. (2012)
	Marus bassanus	Liver	4530±0.451	Nardiello et al. (2019)		*Egretta gularis*	B. feathers	195.1	Mansouri et al. (2012)
	Marus bassanus	Feathers	0.211±0.037	Nardiello et al. (2019)		*Larus heuglini*	B. feathers	178.3	Mansouri et al. (2012)
	Larus heuglini	B. feathers	1.16	Mansouri et al. (2012)	**Cu**	*Egretta gularis*	B. feathers	10.47	Mansouri et al. (2012)
Cu	*Larus heuglini*	B. feathers	4.86	Mansouri et al. (2012)	**Pb**	Little egret chicks	Kidney	8.93±5.5	Kim et al. (2010)
	Gavia arctica	Liver	64.44	Mochizuki et al. (2013)		Night-heron chicks	Liver	0.92±0.73	Kim et al. (2010)

Table 8 (continued)

	Taxon	Categories	Mean or range of means (μg/g)	References		Taxon	Categories	Mean or range of means (μg/g)	References
	Gavia pacifica	Liver	50.64±12.60	Mochizuki et al. (2013)		Night-heron chicks	Kidney	1.19±1.12	Kim et al. (2010)
	Limosa limosa	Liver	231±243	Lucia et al. (2012)		*Buteo buteo*	Kidney	10.8±0.94	Battaglia et al. (2005)
	Limosa limosa	Muscle	41±23	Lucia et al. (2012)		*Athene noctua*	Kidney	2.95±0.42	Battaglia et al. (2005)
	Tadorna ferruginea	Kidney	22.63±8.94	Liu et al. (2020)		Mute swan	Blood	0.028–0.675 (0.239)	Meissner et al. (2020)
Pb	*Tadorna ferruginea*	Kidney	5.82±2.70	Liu et al. (2020)	**Zn**	*Marus bassanus*	Liver	89.81±4205	Nardiello et al. (2019)
	Owl species	Feathers	2.30±1.52	Grúz et al. (2019)		*Marus bassanus*	Kidney	78.65±3589	Nardiello et al. (2019)
	Buzzard	Feathers	1.15±1.40	Grúz et al. (2019)		*Marus bassanus*	Feathers	72.75±3893	Nardiello et al. (2019)
	Common kestrel	Feathers	2.10±1.57	Grúz et al. (2019)		*Larus heuglini*	B. feathers	45.75	Mansouri et al. (2011)
	Eurasian sparrow-hawk	Feathers	1.84±0.92	Grúz et al. (2019)		*Limosa limosa*	Liver	159±75	Lucia et al. (2012)
	Egretta gularis	B. feathers	5.48	Mansouri et al. (2012)		*Limosa limosa*	Muscle	57±22	Lucia et al. (2012)
	Marus bassanus	Liver	0.210±0.027	Nardiello et al. (2019)		Little egret chicks	Liver	46.5±20.4	Kim et al. (2010)
	Marus bassanus	Kidney	0.138±0.018	Nardiello et al. (2019)		Little egret chicks	Kidney	18.5±1.65	Kim et al. (2010)
	Marus bassanus	Feathers	0.399±0.048	Nardiello et al. (2019)		Night-heron chicks	Liver	65.2±12.5	Kim et al. (2010)
	Larus heuglini	B. feathers	7.04	Mansouri et al. (2012)		Night-heron chicks	Kidney	17.4±5.18	Kim et al. (2010)
	Limosa limosa	Liver	0.18±0.26	Lucia et al. (2012)		*Tadorna ferruginea*	Kidney	116.67±63.19	Liu et al. (2020)
	Limosa limosa	Muscle	0.02±0.01	Lucia et al. (2012)	**Co**	*Egretta gularis*	B. feathers	0.69	Mansouri et al. (2012)
	Little egret chicks	Liver	2.78±4.06	Kim et al. (2010)		*Larus heuglini*	B. feathers	0.5	Mansouri et al. (2012)

B. feathers, breast feathers; P. feathers, primary feathers

the amount of reactive oxygen species (ROS) (Stohs and Bagchi 1995; Valko et al. 2005). Oxidative stress associated with metals(loids) has been studied to a lesser extent in free-living birds in nature. The effects of metal-induced oxidative stress have been studied in waterfowl, including *Aythya affinis* (Custer et al. 2000), *Melanitta perspicillata*, and *Oxyura jamaicensis* (Hoffman et al. 1998). In terrestrial species, Yang et al. (2020) have shown that heavy metals accumulated in *Passer montanus* testes negatively affect some basic indicators of male reproductive function. They also suggested that testicular and reproductive hormones play an important role for better sperm production in male *Passer montanus* individuals exposed to environments contaminated with heavy metals. Berglund et al. (2007) showed that antioxidant molecules and lipid peroxidation are useful biomarkers in measuring oxidative stress caused by metal accumulation in juvenile individuals of the *Ficedula hypoleuca* species. Isaksson et al. (2005) compared the plasma levels of carotenoid and glutathione in individuals belonging to the *Parus major* in rural and urban areas. They determined that individuals in urban areas have higher oxidative stress and paler coloration than rural individuals (Isaksson et al. 2005). Metals such as essential metals, aluminum (Al), copper (Cu), manganese (Mn), zinc (Zn), and iron (Fe) are essential in the life cycle of living things (growth, feather formation, reproduction, etc.) (Franson et al. 2012). However, high doses of these essential elements can cause toxic effects on the kidneys and reduce reproduction (Heinz et al. 1989a, 1989b;

Table 9 The most cited studies in the relevant topics

First author (no of total authors)	Title	Journals (impact factor)	Year	TGCS	GCS/Y	GOCS
Scheuhammer, A.M. (1)	The chronic toxicity of aluminum, cadmium, mercury, and lead in birds: A review	Environmental Pollution (6.792)	1987	617	18.70	863
Furness, R.W. (2)	Seabirds as monitors of the marine environment	ICES Journal of Marine Science (3.188)	1997	408	17.73	742
Fry, D.M. (1)	Reproductive effects in birds exposed to pesticides and industrial chemicals	Environmental Health Perspectives (8.38)	1995	402	16.08	676
Evers, D.C. (9)	Patterns and interpretation of mercury exposure in freshwater avian communities in northeastern North America	Ecotoxicology (2.535)	2005	225	15.00	313
Bustamante, P. (4)	Cephalopods as a vector for the transfer of cadmium to top marine predators in the north-east Atlantic Ocean	Science of the Total Environment (6.551)	1998	208	9.45	263
Dauwe, T. (5)	Variation of heavy metals within and among feathers of birds of prey: Effects of molt and external contamination	Environmental Pollution (6.792)	2003	169	9.94	249
Burger, J. (2)	Metal levels in feathers of 12 species of seabirds from Midway Atoll in the northern Pacific Ocean	Science of the Total Environment (6.551)	2000	162	8.10	237
Dauwe, T. (5)	Can excrement and feathers of nestling songbirds be used as biomonitors for heavy metal pollution?	Archives of Environmental Contamination and Toxicology (2240)	2000	159	7.95	197
Honda, K. (3)	Distribution of heavy metals and their age-related changes in the eastern great white egret, (*Egretta alba*) modesta, in Korea	Archives of Environmental Contamination and Toxicology (2240)	1986	143	4.20	216
Goede, A.A. (2)	The use of bird feather parts as a monitor for metal pollution	Environmental Pollution. Series B, Chemical and Physical (6.5)	1984	143	3.97	213
Hutton, M. (1)	Accumulation of heavy metals and selenium in three seabird species from the United Kingdom	Environmental Pollution. Series A, Ecological and Biological (5.714)	1981	142	3.64	188
Brasso, R.L. (2)	Effects of mercury exposure on the reproductive success of tree swallows (*Tachycineta bicolor)*	Ecotoxicology (2.535)	2008	134	11.16	200
Burger, J. (1)	Assessment and management of risk to wildlife from cadmium	Science of the Total Environment (6.551)	2008	133	11.08	215
Burger, J. (1)	Heavy metals in avian eggshells: Another excretion method	Journal of Toxicology and Environmental Health (2.653)	1994	132	5.07	168
Eeva, T. (3)	Growth and mortality of nestling great tits (Parus major) and pied flycatchers (Ficedula hypoleuca) in a heavy metal pollution gradient	Oecologia (2.654)	1996	124	5.16	183
Muirhead, S.J. (2)	Heavy metal concentrations in the tissues of seabirds from Gough Island, South Atlantic Ocean	Marine Pollution Bulletin (3.782)	1988	112	3.50	149
Eeva, T. (3)	Air pollution fades the plumage of the Great Tit	Functional Ecology (5.110)	1998	109	4.95	157
Fasola, M. (3)	Heavy metal, organochlorine pesticide, and PCB residues in eggs and feathers of herons breeding in northern Italy	Archives of Environmental Contamination and Toxicology (2240)	1998	102	4.63	129

GOCS, Google Scholar Citation Score; TGCS, Scopus citation score

Carpenter et al., 2004ab. The abovementioned metal(loids) information is also shown in Table 10.

Scientific productivity evaluation using Lotka's law

According to the documents retrieved, 1000 authors were included for assessment. The distribution of the frequency of authors and the number of their publications was fitted with the Lotka's law (Kulak et al. 2019). For that context, we used Lotka's law of scientific productivity fitting observed frequency data to the power law distribution as y = C/(x^n); $n =$ 1.76770575; C = 0.51607325. Herewith the findings, the C value was calculated as 0.5160. According to this result, 51.6% of those who write articles on this subject are expected to have a single article, and this value was calculated from the collected data.

This result can be considered an estimate; this rate will be valid if all articles written or written on this subject in the world are reached. Lotka suggested a value of approximately $(6/\pi^2) = 0.6079$ for the C value, meaning that the rate of those who publish an article is 60% of all publications. According to the Kolmogorov-Smirnov goodness-of-fit test, the number of

Table 10 The details of the relevant studies reporting harmful effects of metals to birds

Heavy metals	Source	Harmful effects on birds	References
Cadmium (Cd)	Industrial resources such as mining and smelting processes	Chronic exposure of Cd in birds reduces reproductive success and body mass; affects serum testosterone levels and energy metabolism; causes kidney and bone damage; and affects molting, hemoglobin formation and growth, and egg production (*Anas platyrnchos*, *Egretta garzetta*, *Aythya affinis*, *Somateria mollissima*), increasing susceptibility to disease, oxidative stress, and histopathological damage	Nicholson et al. (1983) Scheuhammer (1987), Burger et al. 1992a, 1992bStohs and Bagchi (1995), Wayland et al. (2002), Espejo et al. (2018), Järup and Åkesson (2009), Ding et al. (2020), Cinar (2003)
Copper (Cu)	Natural resources (volcanoes, forest fires) and anthropogenic sources (nonferrous metal production, copper smelting plants, iron and steel production, municipal incinerators)	High amounts of Cu can reduce egg production, kidney function, body and tissue weight, and feather growth in birds. Many bird species have been shown to have higher liver Cu concentrations in young birds than in adult birds. Cu may cause oxidative stress and intracellular oxidative damage by increasing ROS formation	Heinz et al. 1989a, 1989b), Carpenter et al. (2004a, 2004b), Stohs and Bagchi (1995), Barceloux and Barceloux (1999)
Lead (Pb)	Hunting activities, natural Pb emissions originate from volcanoes, forest fires, and biogenic sources	High amount of lead causes physiological stress (*Cygnus olor*), affects brood growth and survival, weight loss, diarrhea, anorexia, hemolytic anemia, poisoning (*Grus canadensis*, *Phoebastria immutabilis*, *Aquila chrysaetos*, *Haliaeetus pelagicus*, *Haliaeetus albicilla*), infection and death (*Gymnogyps californianus*), reproduction (*Zenaida macro*), and behavioral disorders. It negatively affects egg production by reducing the amount of Ca (calcium) in plasma	Meissner et al. (2020), Pain et al. (2009), Pattee et al. (1981), Fisher et al. (2006a, 2006b), Pain and Rattner (1988), Burger and Gochfeld (1994), Mateo et al. (2003), Scheuhammer (1987), Ding et al. (2020), Pain (1992), Finkelstein et al. (2003), Meretsky et al. (2000), Snyder and Snyder (2000)
Mercury (Hg)	Natural resources (geothermal and volcanic activities) and anthropogenic resources (metal and cement production, forest fires, burning of coal and fossil fuels)	Hg accumulation causes immune system disorder (*Phoebastria nigripes*), population decline (*Pagophila eburnea*), death, disability, reproductive impairment (*Gavia immer*), loss of body mass and sensation, prolongation of the incubation period (*Diomedea exulans*), changes in kidney structure and function, and behavioral disorders	Stankovic et al. (2014), Boening (2000), Bond et al. (2015), Dietz et al. (2013), Finkelstein et al. (2007) Goutte et al. (2014a, 2014b), Tartu et al. (2015), Newth et al. (2013)
Heavy metals	Source	Harmful effects on birds	References
Arsenic (As)	Volcanism, forest fires, hydrothermal activities	As accumulation causes reproductive and juvenile development (*Ficedula hypoleuca*, *Parus major*), liver obstruction, necrosis and fibrosis, brain degeneration, delayed ovulation, decrease in egg weight, thinning of the eggshell, behavioral disorder (*Anas platyrhynchos*), tarsis and structural disorders in wings (*Ficedula hypoleuca*), and discoloration of the wings (*Parus major*)	Islam et al. (2009), Janssens et al. (2003), Koivula et al. (2011), Eeva and Lehikoinen (2004), Eeva et al. (1998), Stanley et al. (1994), Camardese et al. (1990), Chen and Chiou (2001), Stankovic et al. (2014)
Chromium (Cr)	Ore refining, Cement producing facilities, İndustrial activities	Cr accumulation can cause mutagenic, teratogenic, and carcinogenic effects in different bird species. It reduces the number of offspring hatched (*Sterna dougallii*, *Larus argentatus*, *Anas rubripes*) and has growth inhibitory effects	Outridge and Scheuhammer (1993), Burger (1994), Eisler (2000)

*Those values were retrieved from INCHEM (Internationally Chemical) (http://www.inchem.org/)

observed authors and the number of authors calculated from Lotka are the same in distribution ($z = 973$ $p = 300$; $p > 0.05$), meaning that the number of authors and number of articles are in accordance with Lotka law.

Along with the findings of the bibliometric analysis, following outcomes were suggested. In this bibliometric study, 971 documents focused on the relationship between heavy metal accumulation and birds and published in the journals scanned in the Scopus database were analyzed.

Articles are the most common type among the published documents, followed by review, conference paper, technical note, short questionnaire, and book chapters. Herewith, we should note that the lowest number regarding book chapters might be related to the disseminating publishing house, which might not be indexed by SCOPUS. Because of the fact that the relevant documents were only extracted from SCOPUS, documents in non-indexed related books or their chapters have not been considered for the present study.

Most of the documents were written in English. The history of the related documents dates from the 1970s to the present. The number of studies on heavy metal accumulation and birds has increased in the last 20 years. The number of documents published between 1970s and the mid-1990s which was the milestone of studies on the subject fluctuated.

The number of citations is important to draw attention to the scientific level of publications. The results indicated that citations particularly are not directly related to the number of publications. The best performance among the number of publications and related citations was obtained by the UK and Canada, followed by Belgium, Norway, and Japan. The top two countries (UK and Canada) with the most citations to their studies produced relatively few publications compared to the USA and Spain. However, the studies have probably been carried out by scientific institutions that have a better scientific reputation or are studying on innovative topics which are of greater interest to other researchers on this topic (Kulak et al. 2019; Raparelli and Lolletti 2020).

Of the selected 34 organizations, the USA was dominant with 5 departments or institutions. "Environmental and Occupational Health Sciences Institute, Piscataway, New Jersey, USA" has stood its first place with 28 publications (2.88%). A total of 73 publications were produced by USA-based organizations or institutes. The number of publications indicated that the USA has the most productive organizations.

The minimum number of scientific papers published by an author was accepted as 5 documents to obtain the co-authorship network map. Sixty-nine of the 2511 authors who conducted scientific studies on this subject met this threshold (minimum five documents). The five authors with the highest number of publications are "Burger J. (66 publications)," "Gochfeld M. (47 publications)," "Eeva T. (35 publications)," "Eens M. (25 publications)," and "Kim J. (22 publications)."

The accumulation of heavy metal contaminants in the bird organs and the negative consequences of the heavy metal accumulation were thoroughly examined based on the co-occurrence terms derived from 971 documents related to the current subject of the study. The term analysis of all documents included in the study was performed. The minimum number of repetitions of the terms was considered 15 and 269 (57%) out of 470 terms met this threshold. Accordingly, *Parus major* (Pariidea), *Ficedula hypoleuca* (Muscicapidae), *Anas platyrhynchos* (Anatidae), *Nycticorax nycticorax* (Ardeidae), *Egretta garzetta* (Ardeidae), *Larus argentatus* (Laridae), *Ciconia ciconia* (Ciconiidae), *Milvus migrans* (Accipitridae), and *Ardea cinerea* (Ardeidae) were the most commonly investigated bird species.

Keyword formation analysis and clustering are useful methods used to obtain better understanding for the extent of the research topics (Kulak et al. 2019). Keyword analysis of the documents related to the subject was carried out and 8 clusters were identified. However, 4 clusters were obtained based on keywords. These were (i) tissue and organ groups in which metal pollutants accumulate, (ii) bird species including aquatic and terrestrial bird taxa, (iii) adverse effects of metal contaminants on birds, and (iv) heavy metal groups including essential and nonessential metals.

Birds were deemed as biomonitors for environmental pollution monitoring as of the early 1990s. Birds were used as bioindicators for measuring pollution parameters in different ecosystems due to their intertwined lifestyle with humans and their distribution over large geographic areas. However, one disadvantage of birds to be used in pollution monitoring is the presence of some migratory species and the difficulty of determining where contamination has occurred (Burger and Gochfeld 2004). Of the conducted studies, the bird species studied were local (resident) in the research areas. The first studies regarding metal pollution were pointed on especially predatory birds, waterfowls, and seabirds. In order to monitor aquatic ecosystems, various researchers, e.g., *Catharacta skua* (Furness and Hutton 1979), *Larus argentatus*, *Sterna hirundo* (Thompson et al. 1993), Seabirds (book chapter Monteiro and Furness 1995), *Diomedea immutabilis*, *Diomedea nigripes* (Burger and Gochfeld 2000), *Nycticorax nycticorax* (Kim and Koo 2007), *Egretta garzetta* (Manjula et al. 2015), *Tadorna ferruginea* (Liu et al. 2020), *Amaurornis phoenicurus*, *Gallinula chloropus* (Mukhtar et al. 2020), *Falco mexicanus*, *Falco columbarius* (Fimreite et al. 1970), *Falco sparverius* (Lincer and McDuffie 1974), *Falco tinnunculus* (Gruz et al. 2019), *Buteo buteo* (Gruz et al. 2019; Naccari et al. 2009), *Upupa epops* (Ahmadpour et al. 2016), and *Passer montanus* (Ding et al. 2020; Pan et al. 2008), have been reported. In the 1990s, many passerine species were used more frequently for monitoring and evaluation of pollution in areas close to various metal industries and in areas with high urbanization, e.g., *Parus major* (Dauwe and

Eens 2008; Dauwe et al. 2006; Eeva and Lehikoinen 1996, 1998; Eeva et al. 2009; Janssens et al. 2001; Snoeijs et al. 2004), *Passer montanus* (Ding et al.2020), *Cyanistes caeruleus* (Eeva et al. 2009), *Ficedula hypoleuca* (Berglund et al. 2010; Eeva and Lehikoinen 1996, 1998).

Bibliometric analysis revealed that seabird, gull, and raptors were of the commonly monitored species for relevant analysis. We also observed that colonial waterfowls (herons, pelicans, cormorants, gulls, and seabirds) have often been used to determine metal(loid) levels or have been proposed for future studies. Many toxic metals(loids) (Cr, Mn, Cu, Zn, As, Se, Rb, Sr, Mo, Ag, Cd, Hg) have been well studied in various terrestrial, aquatic, and sea birds (Dauwe et al. 2005; Ding et al. 2019; Kim and Koo 2007; Nardiello et al. 2019; Soliman et al. 2020). In the last decade, studies regarding lead (Pb) have not been only addressed on predatory birds (Andreotti et al. 2018; Helander et al. 2009; Kanstrup et al. 2019; Krone et al. 2009; Krüger and Amar 2018; Pain et al. 2009; Van den Heever et al. 2019) but also on other wild bird species (Ecke et al. 2017; Pain et al. 2019; Nadjafzadeh et al. 2013; Van den Heever et al. 2019; Yaw et al. 2017). In addition, it has been documented that of the killed hunting animals, predators and vultures were exposed to lead fragments from rifle ammunition in offal or carcasses (Helander et al. 2009; Krone et al. 2009).

Birds have been used successfully to identify temporal and spatial trends in toxic metal pollution in terrestrial and aquatic ecosystems (Bauerova et al. 2020; Berglund et al. 2011; Burger and Gochfeld 2004; Deng et al. 2007; Hargreaves et al. 2011; Kitowski et al. 2012; Zhang and Ma 2011). In the review study by Burger (2006), most of the studies cited were oriented on metal contamination and bioindicator issue (Stankovic and Stankovic 2013.

According to the score of relevance and occurrence, biomonitoring was of the mostly used terms. In aquatic and terrestrial ecosystems, fish (Zeitoun and Mehana 2014), plants (Devries et al. 2002; Nagajyoti et al.2010) invertebrates (Stankovic and Stankovic 2013; Stankovic and Stankovic 2013), mammals (Kalisinska et al. 2012), and birds (Burger and Gochfeld 1993; Dauwe et al.2005, Dauwe et al.2006; Ding et al. 2020; Gruz et al. 2019) are of the notable living organisms used for the relevant researches. But, in recent years, it has been observed that birds are predominantly used in environmental metal pollution monitoring studies. It has been observed that metal pollutants accumulate in many wild species and cause serious problems (Al-Othman and Naushad 2011; Gruz et al. 2019; Nagajyoti et al. 2010; Reilly 1991; Zeitoun and Mehana 2014). Pollutants enter the body by inhaling the polluted air directly, drinking polluted water, and ingesting food consisting of plants that grow in contaminated soil that has direct contact with the soil (Bhagure and Mirgane 2011; Dudka and Miller 1999). Metals were first observed to accumulate in the liver by interacting with metal-binding proteins such as metallothionein until they reach the accumulation threshold, and then the metal protein complex reached the kidney via plasma and accumulated over time (Adham et al. 2011). The kidney and liver are the organs with the highest concentration of metal in vertebrates (Adham et al. 2011). Birds, as in the vertebrate class, have been well studied in the literature on the subject where they accumulate metals and metalloids in various organs or tissues (Cardiel et al. 2011; Durmuş 2018; Durmuş et al. 2018; Llacuna et al. 1995; Nergiz and Şamat 2019; Tanaka et al. 2020; Van den Steen et al. 2007; Zarrintab and Mirzaei 2018). Of the studies, most of them have been carried out with egg (shell, content), blood, feather, liver, and kidney tissues. Furthermore, the brain, pancreas, bone, feces, and cadavers were also analyzed. In most bird studies, it has been observed that toxic element concentrations are mostly accumulated in tissues such as the liver or kidney (Beyer et al. 2004; Binkowski and Meissner 2013; Campbell et al. 2005; Eisler 2010; Garcá-Fernández et al. 1996; Nardiello et al. 2019; Shore et al. 2011). Cadmium (Cd) is a powerful nephrotoxin and 75% of the body load accumulates in the liver and kidneys (Binkowski and Meissner 2013). Concentrations in these organs are used as indicators of the organism's exposure to this metal. Garcá-Fernández et al. (1996) reported that the element cadmium first accumulates in the kidney, then the liver, and to a lesser extent in the brain and bone as the organ of accumulation. In the study Nardiello et al. (2019), highest concentration of As, Hg, and Zn was accumulated in the liver and Cd was mostly accumulated in the kidney of *Morus bassanus*. After intake of mercury (Hg), it is stored in internal tissues such as the kidney and liver and thrown out of the body by feathers and eggs (Kitowski et al. 2012). Accumulation of metals(loids) in internal organs or tissues can cause morbidity, toxicity, and mortality, causing a decrease in population demography.

Along with the long years, adverse impacts of metal(loid)s on birds have been well and widely discussed. Those impacts were also addressed in keyword and terms, such as oxidative stress (Berglund et al. 2007; Custer et al. 2006; Espin et al. 2014a, b; Koivula et al.2011; Martinez-Haro et al. 2011), physiological stress (Meissner et al.2020), organ damage (Espejo et al.2018), behavioral disorder (Ding et al. 2020; Espejo et al. 2018), poisoning (Pain 1992; Scheuhammer and Norris 1996), thinning of eggshells (Espejo et al.2018), egg laying intervals (Dauwe et al. 2005; Janssens et al. 2003) and increased incubation time (Fisher et al. 2006a; Kubiak et al. 1989), offspring death (Berglund et al.2010; Bel'skii et al.2005), and egg size and decline in quality (Eeva and Lehikoinen 1995;Eeva et al. 2009; Janssens et al. 2003). In addition to these direct effects, heavy metal pollution has been reported to inhibit reproductive success by reducing food sources, affecting pre-breeding birds body size, weight, and fat reserves (Ai et al. 2019; Borgå et al. 2001; Burger 1995; Dauwe et al. 2006; Ding et al. 2019, 2020; Martin 1987). It has been observed that birds accumulate some metals(loids) more in their bodies with age. In adult birds, the accumulation of some metal(loid) levels in the inner tissues may increase over time (Burger 1994; Furness and Camphuysen 1997; Furness and Monaghan 1987; Mansouri et al. 2012). The difference in metal levels between adult and juvenile birds may also occur with food variety or sizes (Ai et al. 2019; Burger 1996). Barbieri et al. (2010) reported that the levels of Cd, Co, Cr, Mn, Ni, Zn, and Pb in the feathers of the *Larus dominicanus* increased with age. Ni, Cu, Se, and Hg metal levels in adult individuals of *Ciconia ciconia* were higher than their offspring, while the Pb level was lower (Maia et al. 2017). Similarly, an increase in metal levels of *Passer montanus* due to the increase in maturity level was reported (Pan et al. 2008). Also, Hg levels in adult individuals were higher than the young individuals in the reproductive period (Perkins et al. 2016). Zarrintab and Mirzael (2018) reported that Pb, Cd, and Ni levels in the liver, kidneys, and muscles of *Pica pica* showed higher accumulation in adults compared to juvenile individuals. Naccari et al. (2009) reported that there are differences in metal concentrations between young and adult individuals of hawks (Common buzzard), while Burger and Gochfeld (1993) found that lead (Pb), cadmium (Cd), chromium (Cr), selenium (Se), and manganese (Mn) levels in adult individuals of large egrets are significant compared to young individuals and there was little difference between mercury levels. Nardiello et al. (2019) reported that metal levels in the hair, kidney, and liver tissues of *Morus bassanus* increased with age. Burger (1995) reported that the levels of cadmium and lead in the feathers of Franklin gulls are higher in adults. According to Furness and Monaghan (1987), cadmium concentration is always higher in adults due to bioaccumulation. The accumulation lasts for years just being first accumulated in blood and then in the hair (Norouzi et al. 2012). While Mansouri et al. (2012) reported higher cadmium and lead levels in adult individuals of *Egretta gularis* and *Larus heuglini* than their offspring, Meissner et al. (2020) compared the amount of lead in the blood of adult and young *Cygnus olor* individuals and reported higher levels in juveniles. Kucharska et al. (2019) reported that the Hg level in the blood tissues of *Cygnus olor* showed significant differences between adults and young individuals. Gochfeld et al. (1996) reported that in *Larus atricilla* species, Hg decreases in the hair and heart with age; Pb increases in the heart, liver, and kidney; Cd level increases in the hair, heart, liver, and muscles; and Cr in liver and heart with age. The accumulation of metals depending the age, especially in hair, has been well-reported in most seabirds (Barbieri et al. 2010; Burger 1995; Burger and Gochfeld 2000; Mansouri et al. 2012; Mendes et al. 2008; Pan et al. 2008; Saeki et al. 2000; Yamamoto et al. 1996). However, some studies have reported no significant change in metal accumulation levels with age (Gruz et al. 2019; Hoshyari et al. 2012; Movalli 2000; Wayland and Bollinger 1999; Zarrintab et al. 2016). It is worthy to note herein that bioaccumulation of metal(loid)s have not been widely studied in comparison of genders (Burger 1995; Mansouri et al. 2012; Zamani-Ahmadmahmoodi et al. 2009). Although gender- and age-related differences have been reported for a large number of species, there is no clear pattern regarding the elements or tissues. This is thought to be due to the insufficient number of specimens or the inability to determine the exact age or gender of the birds.

Of the terms extracted from the documents relevant, feathers are of the most commonly used term with high relevance score. In that context, we observed that the most sampling in birds was done on feathers in the studies regarding with metal pollution. Factors such as easy collection and storage of feathers reduce the cost of sampling. Also, studying with feathers is a nondestructive and noninvasive sampling type. Although feathers can help analyze pollution dynamics in different ecosystems, some situations may not represent the body burden of metals(loids) (Berglund et al. 2011). The common idea in relevant studies regarding feather sampling is the opinion that feathers are a good indicator of metal(loid) contamination. Feathers with content of metal and metalloids contain represent the body level well during hair growth, during the development of young individuals, or during molting. At the same time, feathers are an important tool in determining long-term and spatial trends of Hg contamination.

In some of the studies on metal accumulation in feathers, it was observed that Fe and Hg levels were found to be higher since Fe is required for feather formation in birds in early breeding (Osborn et al. 1979). Feathers play an important role in excretion of a significant portion of the Hg load in the body (Whitney and Cristol 2017), contributing to lower content of Hg in inner tissues (Braune and Gaskin 1987; Hughes et al. 1997). Many metal and metalloid concentrations in feathers provide useful information about the extent of exogenous contamination. Breast feathers in birds are used more to measure pollution levels, as they are less affected by molting than flight feathers (Burger and Gochfeld 2000; Mansouri et al. 2012).

Feather patterns may vary depending on the years or seasons; therefore, pre-breeding or seasonal differences should be taken into account in feather sampling. Gender- and age-related differences have been reported for a large number of species. However, no clear pattern regarding the elements or textures has been documented. This may be attributed to insufficient sampling or difficulty in determining the exact age or sex of birds (Burger and Gochfeld 1999; Gochfeld et al. 1996).

Birds are abundant and in some cases long-lived organisms with a continental distribution. Birds on the upper steps of the food chain also play a key role in the continuity of the trophic food flow. Considering all these situations, birds are exposed to more pollutants than other living things. Therefore, many bird species are indicator organisms that allow comparisons between different ecosystems, countries, and even continents.

Birds have often been used to monitor local pollution as well as compare exposures of migratory species in different regions.

Along with the present study, we, for the first time, reported a bibliometric analysis using VOSviewer software and provided a comprehensive content analysis of studies concerned with metal(loids) accumulation and bird studies. In that context, term, keyword, authors, country, and citation analysis of the relevant documents were reported, providing the gaps in the relevant areas for the further studies.

Future outlook and the way forward

Metals have a direct and indirect deleterious effect on organisms. Metal pollution indirectly affects wildlife by changing food chains, habitats, population dynamics, and ecological interactions between species. Birds are located at the top of the food chain and spread over wide geographical areas; therefore, they are exposed to pollutants higher compared to the other creatures. Numerous studies indicated that exposure to metals or metalloids causes various neurological, physiological, reproductive, developmental, and behavioral disorders in birds. However, the circumstances of oxidative stress in birds or the primary causes of this condition related to heavy metal pollution have not been clearly understood. Few studies have focused on the antioxidant activities and lipid peroxidation as useful biomarkers to measure the oxidative stress in living organisms in relation to metal concentrations. However, the studies on which tissues or organs trigger the oxidative stress under metal accumulation are missing in the literature. In addition, dose-response–based studies investigating the tolerable As (Arsenic) and other metal levels depending on age and gender should be carried out. Understanding the effects of oxidative stress on both the individual and population level is also an important step to develop effective conservation strategies for at-risk species. In addition, more information is needed regarding the effects of heavy metal contamination on DNA repair mechanism, nucleotide base insertions, and the transmission of DNA damage that may occur due to the contaminants to the next generation.

Metal exposure of birds occurs through feeding and breathing. However, most of the studies focused on nutritional exposure, while inhalation exposure was ignored. Another important issue is lead poisoning. The concentrations reported in the papers reviewed revealed that the lead can cause serious health problems or death in many different bird species. Hunting activity, which is common in everywhere in the world, can cause lead accumulation in birds and their habitats. In particular, vultures that feed on offal from animals injured or killed by lead ammunition are the most affected bird species. Further research is needed to assess the impact of this pollutant on vulture demography. Therefore, the populations of some vulture species may significantly decrease. In addition, research is needed the impacts of heavy metals such as lead and cadmium on genetic diversity in birds. Limited number of studies, conducted on this subject, reported that the genetic diversity among the same species decreases, especially when metals such as lead and cadmium excessively accumulate in the body. Therefore, such studies should be carried out more frequently in the industrialized countries.

Conclusion

This is the first study providing a bibliometric analysis of research trends in documents on the effects of heavy metal pollution or accumulation on birds between 1970 and May 2020. The most important results of this study are as follows:

(1) The documents published between 1970 and May 2020 were examined. Accordingly, the number of annual publications has significantly increased after 1995 and reached the peak with 47 articles published in 2018. The number of documents published between 1974 and 1994 fluctuated, whereas the number of articles published annually between 1995 and May 2020 was constant and double digits. The highest percentage of annual citations to total documents was recorded in 1987 and 1992.

(2) The highest number of documents on the subject was published by the USA, followed by Spain, Canada, China, and the UK.

(3) The UK and Canada had the best performance in the total number of citations to the published documents, while the USA and Spain that published the most documents did not show the same success in the number of citations.

(4) Another important result of the study is that citations are not directly related to the number of publications. The results can be associated with the fact that the subjects or techniques used in the studies contribute to the number of citations.

(5) The distribution of the frequency of authors and the number of their publications was fitted with the Lotka's law. Kolmogorov-Smirnov goodness-of-fit test results showed that there were no differences between theoretical (expected) and observed authors numbers.

(6) All documents are original studies. In general, the most cited documents are reviews and conference proceedings.

(7) The most studied bird taxa are *Paridea*, *Ardeidea*, *Anatidea*, *Laridea*, and *Accipitridea*.

(8) Four clusters were formed in the term analysis. The clusters were (i) tissue and organ groups in which metal pollutants accumulated, (ii) bird species including aquatic and terrestrial bird taxa, (iii) adverse impacts of metal

contaminants on birds, and (iv) essential and nonessential heavy metal groups.

(9) The highest number of documents on the subject was published in "Science of the Total Environment" journal followed by "Archives of Environmental Contamination and Toxicology," "Environmental Monitoring and Assessment," and "Environmental Pollution" journals.

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Authors' contributions Emrah Celik (EC) designed the study and conceived the original idea for the manuscript. He is also in charge of writing the main manuscript including figures and tables. EC, Atilla Durmus, Ozdemir Adizel, and Humeyra Nergiz participated in the revision of the final manuscript and approved it.

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