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Global prevalence of *Toxoplasma gondii* in birds: A systematic review and meta-analysis

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A R T I C L E I N F O

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A B S T R A C T

Among the potential animal reservoirs of the zoonotic parasite *T. gondii*, birds have received relatively little attention. This systematic review and meta-analysis aimed to assess the global status and to provide an overview of the epidemiology of *T. gondii* infection in birds. The standard protocol of preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were followed. Scopus, PubMed, Web of Science, Science Direct, ProQuest, and Google Scholar were searched for relevant publications from January 1990, to March 2024. All peer-reviewed original research articles describing the prevalence of *T. gondii* in birds were included. Inclusion and exclusion criteria were applied, and both direct and indirect detection were considered. The point estimates and 95% confidence intervals were calculated using the meta-package in R (version 3.6.1). The variance between studies (heterogeneity) was quantified by the I^2 index. Finally, 258 articles (including 380 datasets) were eligible for inclusion in the systematic review and meta-analysis. The global pooled prevalence was 24% (21 - 26%). The highest prevalence of *T. gondii* was observed in buzzards (52%, 34 - 70%), turkeys (31%, 17 - 46%), and chickens (30%, 26 - 34%). The present study provides a comprehensive view of the global prevalence of *T. gondii* in birds.

1. Introduction

The protozoan *Toxoplasma gondii* (*T. gondii*), the causative agent of toxoplasmosis, is one of the most successful parasites and can infect humans and almost all warm-blooded animals globally Dubey et al., 2020; Zaki et al., 2020a; Abbasali et al., 2023). It is a major

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public health issue, and it is estimated that nearly a third of the world's human population is infected (Dubey, 2008; Dubey et al., 2020). Members of the Felidae family, both wild and domestic felids, are the definitive hosts in the life cycle of *T. gondii*, while other animals, including birds, can serve as intermediate hosts. All hosts can acquire the infection by ingesting tissues of infected hosts or ingesting infective oocysts, originally shed in the feces of cats (Rahimi et al., 2015). Humans are no exception; this parasitic infection may be transmitted to humans via drinking contaminated water, ingestion of contaminated food, or eating raw or undercooked meat of infected animals, including birds (Dubey, 2010; Foroutan et al., 2019), or raw eggs (Dubey, 2010; Khademi et al., 2018). Vertical transmission of *T. gondii* infection can also occur in several host species (Cabezon et al., 2016; Dubey et al., 2020; Foroutan et al., 2018). Also, infection via blood transfusion and organ transplantation are other possible routes of transmission (Foroutan et al., 2018; Zaki et al., 2020b).

The outcomes of *T. gondii* infection vary according to host and parasite factors, in particular the immune status of the host (Wilson et al., 2020). In immunocompetent individuals, *T. gondii* infection is oftentimes subclinical or mild. However, especially in those with compromised immune systems, toxoplasmosis can cause widespread complications and life-threatening outcomes (Wilson et al., 2020). The disease can be severe in birds, with e.g., pneumonia, splenitis, hepatitis, multi-organ involvement, and even death (Jokelainen and Vikøren, 2014).

The role of birds in the spread and transfer of infectious agents is obvious. They are considered good carriers or reservoirs for infectious agents due to their high dispersal capabilities. According to the published literature, *T. gondii* prevalence has increased in several bird species (Cooper et al., 2015; Dubey, 2002; Dubey et al., 2010; Karshima et al., 2020; Nie et al., 2022).

Toxoplasma gondii is recognized as a significant causative agent of mortality among diverse species of birds (Tian et al., 2012). Birds play a crucial role as intermediate hosts for *T. gondii*, and their infection with this parasite holds significant epidemiological importance. Specifically, when ground-feeding birds become infected with *T. gondii*, it signifies the potential contamination of soil with oocysts, which in turn serves as a source of infection for cats (Gondim et al., 2010). Certain opportunistic birds, such as seagulls, serve as reliable indicators of environmental contamination because they rely on dumps and sewage systems for their food sources (Lopes et al., 2021). Moreover, birds frequently preyed upon by felines may be regarded as significant reservoirs of *T. gondii*. These infected birds, harboring tissue cysts, pose a potential risk of transmitting the infection to both humans and cats (Bata et al., 2021). Especially, game birds, if not adequately cooked, present a potential risk of transmitting *T. gondii* to humans who consume them (Lopes et al., 2021).

Toxoplasma gondii is a parasite that needs to be addressed using a One Health approach (Nardoni et al., 2019). Its hosts include birds and mammals, including humans (Delgado et al., 2022; Dubey et al., 2010). In addition, oocysts of the parasite can contaminate the environment, water, and soil (Maleki et al., 2020). For many birds, most *T. gondii* infections are presumably transmitted via contaminated feed, water or soil (Shapiro et al., 2019). Indeed, infected birds have been demonstrated to be a candidate group of sentinel animals to reveal environmental contamination with *T. gondii* oocysts (Cabezon et al., 2011).

Toxoplasma gondii has been the subject of much study on mammals, especially humans and domestic animals, although, there is a gap of knowledge on the global prevalence of the parasite in bird populations. The present systematic review and meta-analysis focusing on *T. gondii* in birds may shed light into the parasite's distribution patterns, transmission dynamics, and potential risks to humans and animals. Furthermore, such a study could pinpoint areas with high infection rates and elucidate the factors influencing the transmission of *T. gondii*. This knowledge is essential for developing effective strategies to control the spread of the parasite and reduce its impact on both human and animal populations.

2. Materials and methods

2.1. Information sources and systematic search

The present systematic review and meta-analysis was done according to the preferred reporting items for systematic reviews and meta-analysis (PRISMA) statement (Moher et al., 2009). Literature search for published studies on the prevalence of *T. gondii* infection in birds was retrieved via searching six international databases Scopus, PubMed, Web of Science, Science Direct, ProQuest, and Google Scholar) between 1990 and 01 March 2024. The search process was accomplished using the conjunction of the following key words: ("*Toxoplasma gondii*" OR "*T. gondii*" OR "*Toxoplasma* infection" OR "Toxoplasmosis") AND ("prevalence" OR "epidemiology") AND ("bird" OR "avian" OR "chicken"). Moreover, the bibliographic list of all selected articles and their citing articles were hand-searched to find additional relevant articles.

2.2. Inclusion criteria, study selection and data extraction

The first selection of studies was made based on information specified in the title and abstract. The second step was to verify the full text of the article, if available. Studies were included if they met the pre-established criteria: (1) full-texts or abstracts published in English without geographical limitation, (2) peer-reviewed original research articles, short reports or letters to the Editor that studied the prevalence of *T. gondii* in birds, (3) papers published online from January 1990, until March 2024 with a digital object identifier (DOI), and (4) those papers that provided the exact total sample size and number of samples that tested positive. Papers not meeting the above-mentioned criteria were excluded. Moreover, we excluded studies with a sample size fewer than twenty and if there were less than three articles available based on each species of bird.

The included data were gathered using a Microsoft Excel spreadsheet for the following sub-terms: the author's name, year of publication, continent, country, types of tested samples (tissue and/or serum), diagnostic method, wild or domestic bird, type of bird,

Table 1
Main characteristics of the included studies reporting the prevalence of *Toxoplasma gondii* in birds

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
1	Peixoto and Lopes	1990	Brazil	South America	NS	Chickens	20	6
2	Ghorbani and Gharavi	1990	Iran	Asia	NS	Chickens	109	33
2	Ghorbani and Gharavi	1990	Iran	Asia	NS	Turkeys	25	6
3	Kirkpatrick et al.	1990	U.S.A	North America	1986 - 1987	Owls	270	30
3	Kirkpatrick et al.	1990	U.S.A	North America	1986 - 1987	Pigeons	34	2
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Sparrows	1907	10
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Sparrows	316	2
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Ducks	184	22
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Ducks	25	7
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Buzzards	123	10
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Pheasants	590	14
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Pigeons	606	6
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Doves	60	3
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Crows	495	89
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Gulls	61	10
4	Uterák et al.	1992	Czech Republic	Europe	1981 - 1990	Starlings	69	1
5	Litera´k and Hejlic	1993	Czech Republic	Europe	1981 - 1990	Chickens	2217	5
5	Litera´k and Hejlic	1993	Czech Republic	Europe	1981 - 1990	Ducks	357	6
5	Litera´k and Hejlic	1993	Czech Republic	Europe	1981 - 1990	Geese	32	5
6	Lindsay et al.	1993	U.S.A	North America	NS	Hawks	27	13
7	Valian and Ebrahimi	1994	Iran	Asia	NS	Pigeons	36	1
7	Valian and Ebrahimi	1994	Iran	Asia	NS	Sparrows	149	21
7	Valian and Ebrahimi	1994	Iran	Asia	NS	Doves	147	5
8	Frenkel et al.	1995	Panama	North America	NS	Doves	79	2
9	Quist et al.	1995	U.S.A	North America	1984-1989	Turkeys	130	13
10	Literák et al.	1997	Czech Republic	Europe	1995-1996	Sparrows	228	28
10	Literák et al.	1997	Czech Republic	Europe	1995-1996	Sparrows	41	2
11	Devada et al.	1998	India	Asia	NS	Chickens	185	73
12	Inci et al.	1998	Turkey	Asia	NS	Chickens	300	5
13	Arene	1999	Nigeria	Africa	NS	Vultures	240	136
14	Dubey et al.	2000	Canada	North America	1995-1997	Ostriches	973	28
15	El-Massry et al.	2000	Egypt	Africa	NS	Turkeys	173	103
15	El-Massry et al.	2000	Egypt	Africa	NS	Chickens	108	51
15	El-Massry et al.	2000	Egypt	Africa	NS	Ducks	48	24
16	Garcia et al.	2000	Brazil	South America	NS	Chickens	155	16
17	Sreekumar et al.	2001	India	Asia	NS	Chickens	46	10
18	Martinez-Diaz et al.	2002	Spain	Europe	1997-2001	Ostriches	117	1
19	Dubey et al.	2002	Brazil	South America	2001	Chickens	82	32
20	Sreekumar et al.	2003	India	Asia	NS	Chickens	741	133
21	Da Silva et al.	2003	Brazil	South America	NS	Chickens	198	129
22	Dubey et al.	2003	Egypt	Africa	NS	Chickens	121	49
23	Dubey et al.	2003	Brazil	South America	NS	Chickens	40	16
24	Dubey et al.	2003	U.S.A	North America	2001-2002	Chickens	118	20
25	Dubey et al.	2003	Argentina	South America	NS	Chickens	29	19
26	Dubey et al.	2004	Israel	Asia	2003	Chickens	96	45
27	Andrzejewska et al.	2004	Poland	Europe	2002-2003	White Storks	249	17
28	Piasecki et al.	2004	Poland	Europe	NS	Pigeons	230	172
29	Dubey et al.	2004	Mexico	North America	2002-2003	Chickens	208	13
30	Dubey et al.	2004	Peru	South America	2003	Chickens	50	14
31	Cicek et al.	2004	Turkey	Asia	NS	Chickens	328	2

(*continued on next page*)

Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
32	Dubey et al.	2005	Democratic Republic of Congo	Africa	NS	Chickens	50	25
32	Dubey et al.	2005	Mali	Africa	NS	Chickens	48	5
32	Dubey et al.	2005	Burkina Faso	Africa	NS	Chickens	40	1
32	Dubey et al.	2005	Kenya	Africa	NS	Chickens	30	4
33	Dubey et al.	2005	Argentina	South America	2004	Chickens	61	25
34	Abrahams-Sandi and Vargas-Brenes	2005	Costa Rica	North America	NS	Chickens	471	191
35	Dubey et al.	2005	Sri Lanka	Asia	2003	Chickens	100	39
36	Hove and Mukaratirwa	2005	Zimbabwe	Africa	2001-2002	Ostriches	50	24
37	Zia-Ali et al.	2005	Iran	Asia	NS	Chickens	45	23
38	Dubey et al.	2005	Australia	Oceania	2004-2005	Chickens	830	302
39	Dubey et al.	2005	Venezuela	South America	NS	Chickens	46	16
40	Dubey et al.	2005	Grenada	North America	NS	Chickens	102	53
41	Dubey et al.	2005	Guatemala	North America	NS	Chickens	50	37
42	Deyab and Hassanein	2005	Egypt	Africa	NS	Chickens	150	28
43	Dubey et al.	2005	Colombia	South America	NS	Chickens	77	32
44	Dubey et al.	2006	chile	South America	NS	Chickens	85	47
45	Asgari et al.	2006	Iran	Asia	2005	Chickens	122	44
46	Dubey et al.	2006	Brazil	South America	2005	Chickens	50	33
47	Tsai et al.	2006	Taiwan	Asia	2004	Pigeons	665	31
48	Brandao et al.	2006	Brazil	South America	2000-2003	Chickens	28	15
49	Dubey et al.	2006	Nicaragua	North America	2005	Chickens	98	84
50	Dubey et al.	2006	Costa Rica	North America	2005	Chickens	144	60
51	Dubey et al.	2006	Portugal	Europe	NS	Chickens	225	61
52	Dubey et al.	2007	Brazil	South America	2006	Chickens	84	39
53	Dubey et al.	2007	Guyana	South America	NS	Chickens	76	50
54	Altinoz et al.	2007	Turkey	Asia	2004-2005	Chickens	287	1
55	Eslami et al.	2007	Iran	Asia	NS	Crows	125	2
56	Murao et al.	2008	Japan	Asia	2004-2005	Ducks	111	35
56	Murao et al.	2008	Japan	Asia	2004-2005	Ducks	58	4
56	Murao et al.	2008	Japan	Asia	2004-2005	Ducks	27	7
56	Murao et al.	2008	Japan	Asia	2004-2005	Geese	123	18
56	Murao et al.	2008	Russia	Europe	2004-2005	Geese	39	9
56	Murao et al.	2008	Russia	Europe	2004-2005	Geese	35	5
57	Asgari et al.	2008	Iran	Asia	2005	Chickens	697	70
58	Zhu et al.	2008	China	Asia	NS	Chickens	518	113
59	Lindstrom et al.	2008	Uganda	Africa	NS	Chickens	85	40
60	Waap et al.	2008	Portugal	Europe	NS	Pigeons	695	32
61	Dubey et al.	2008	Ghana	Africa	2006-2007	Chickens	64	41
61	Dubey et al.	2008	Italy	Europe	2006-2007	Chickens	80	11
61	Dubey et al.	2008	Indonesia	Asia	2006-2007	Chickens	90	24
61	Dubey et al.	2008	Poland	Europe	2006-2007	Chickens	20	6
61	Dubey et al.	2008	Vietnam	Asia	2006-2007	Chickens	330	80
62	Velmurugan et al.	2008	Nigeria	Africa	2005	Chickens	79	5
63	De Oliveira et al.	2009	Brazil	South America	NS	Chickens	152	81
64	Asgari et al.	2009	Iran	Asia	2006	Chickens	231	58
65	Bartova et al.	2009	Czech Republic	Europe	2003-2004	Geese	178	77
65	Bartova et al.	2009	Czech Republic	Europe	2003-2004	Ducks	360	52
65	Bartova et al.	2009	Czech Republic	Europe	2003-2004	Chickens	510	1
66	Butty	2009	Iraq	Asia	2008	Turkeys	107	82
67	Chumpolbanchorn et al.	2009	Thailand	Asia	NS	Chickens	303	194
68	Contente et al.	2009	Brazil	South America	NS	Ostriches	195	28
69	Salant et al.	2009	Israel	Asia	2001-2002	Pigeons	495	20

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
70	Yan et al.	2009	China	Asia	2008	Ducks	349	56
70	Yan et al.	2009	China	Asia	2008	Chickens	605	51
71	Aigner et al.	2010	Brazil	South America	NS	Chickens	65	28
72	Soares et al.	2010	Brazil	South America	NS	Rheas	69	3
73	Deem et al.	2010	Ecuador	South America	2003-2008	Penguins	298	7
74	Dubey et al.	2010	U.S.A	North America	2008-2010	Pigeons	129	5
74	Dubey et al.	2010	U.S.A	North America	2008-2010	Hawks	47	8
74	Dubey et al.	2010	U.S.A	North America	2008-2010	Doves	30	2
74	Dubey et al.	2010	U.S.A	North America	2008-2010	Starlings	27	4
74	Dubey et al.	2010	U.S.A	North America	2008-2010	Hawks	45	5
75	Gondim et al.	2010	Brazil	South America	2007-2008	Sparrows	293	3
76	Sousa et al.	2010	Brazil	South America	NS	Pigeons	120	1
77	Harfoush and Tahoon.	2010	Egypt	Africa	NS	Ducks	58	32
78	Sroka et al.	2010	Poland	Europe	NS	Chickens	173	58
78	Sroka et al.	2010	Poland	Europe	NS	Ducks	33	7
79	Alsanjary et al.	2010	Iraq	Asia	2008	Chickens	150	95
80	Shaapan et al.	2011	Egypt	Africa	2011	Quails	376	104
81	Koethe et al.	2011	Germany	Europe	NS	Turkeys	1913	387
82	AbouLaila et al.	2011	Egypt	Africa	2001-2003	Ducks	151	21
83	Alvarado-Esquive et al.	2011	Mexico	North America	2009-2010	Pigeons	521	7
84	Cabezon et al.	2011	Spain	Europe	1996-2010	Buzzards	96	49
84	Cabezon et al.	2011	Spain	Europe	1996-2010	Vultures	175	31
84	Cabezon et al.	2011	Spain	Europe	1996-2010	Owls	144	98
84	Cabezon et al.	2011	Spain	Europe	1996-2010	Owls	45	6
84	Cabezon et al.	2011	Spain	Europe	1996-2010	Owls	38	5
84	Cabezon et al.	2011	Spain	Europe	1996-2010	White Storks	64	9
85	De Lima et al.	2011	Brazil	South America	NS	Pigeons	238	12
86	Karatepe et al.	2011	Turkey	Asia	2003-2004	Pigeons	216	2
87	Lopes et al.	2011	Portugal	Europe	2008-2010	Buzzards	26	18
88	Vilela et al.	2011	Brazil	South America	NS	Sparrows	151	91
89	Yan et al.	2011	China	Asia	2009-2010	Pigeons	275	24
90	Yan et al.	2011	China	Asia	2007-2009	Geese	274	41
91	Maksimov et al.	2011	Germany	Europe	NS	Ducks	2534	145
91	Maksimov et al.	2011	Germany	Europe	NS	Geese	373	94
92	Huang et al.	2012	China	Asia	NS	Pheasants	98	2
92	Huang et al.	2012	China	Asia	NS	Sparrows	22	1
92	Huang et al.	2012	China	Asia	NS	Sparrows	35	1
93	Alkhaled et al.	2012	Iraq	Asia	2010	Chickens	400	196
93	Alkhaled et al.	2012	Iraq	Asia	2010	Ducks	50	28
94	Ibrahim et al.	2012	Pakistan	Asia	NS	Quails	200	8
94	Ibrahim et al.	2012	Pakistan	Asia	NS	Turkeys	200	32
94	Ibrahim et al.	2012	Pakistan	Asia	NS	Ducks	200	24
94	Ibrahim et al.	2012	Pakistan	Asia	NS	Pigeons	200	16
95	Al-Sanjary and Hussein	2012	Iraq	Asia	NS	Chickens	130	102
96	Waap et al.	2012	Portugal	Europe	2009-2010	Pigeons	1507	39
97	Yang et al.	2012	China	Asia	2012	Chickens	502	37
97	Yang et al.	2012	China	Asia	2012	Ducks	268	26
97	Yang et al.	2012	China	Asia	2012	Geese	128	9
98	Alvarado-Esquivel et al.	2012	Mexico	North America	2011	Chickens	519	36
99	Beltrame et al.	2012	Brazil	South America	2007-2009	Chickens	510	206
100	Cong et al.	2012	China	Asia	2011	Chickens	413	30
100	Cong et al.	2012	China	Asia	2011	Pigeons	312	37

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
100	Cong et al.	2012	China	Asia	2011	Ducks	334	38
101	Costa et al.	2012	Brazil	South America	2007-2010	Chickens	100	80
102	Darwich et al.	2012	Spain	Europe	NS	Vultures	105	1
102	Darwich et al.	2012	Spain	Europe	NS	Magpies	33	5
103	Dwinata et al.	2012	Indonesia	Asia	NS	Chickens	125	31
104	Holsback et al.	2012	Brazil	South America	NS	Chickens	40	27
105	Molina-López et al.	2012	Spain	Europe	2006-2010	Crows	113	91
106	Casartelli-Alves et al.	2012	Brazil	South America	NS	Chickens	220	61
107	Sandstrom et al.	2013	Russia	Europe	2006-2010	Geese	157	28
107	Sandstrom et al.	2013	Svalbard	Europe	2006-2010	Geese	811	120
107	Sandstrom et al.	2013	The Netherlands	Europe	2006-2010	Geese	119	13
107	Sandstrom et al.	2013	The Netherlands	Europe	2006-2010	Geese	38	3
107	Sandstrom et al.	2013	The Netherlands	Europe	2006-2010	Geese	161	3
107	Sandstrom et al.	2013	Svalbard	Europe	2006-2010	Geese	168	11
107	Sandstrom et al.	2013	Denmark	Europe	2006-2010	Geese	405	49
108	Mancianti et al.	2013	Italy	Europe	2011-2012	Ducks	41	3
109	Khademvatan et al.	2013	Iran	Asia	2011	Chickens	103	16
109	Khademvatan et al.	2013	Iran	Asia	2011	Pigeons	43	3
109	Khademvatan et al.	2013	Iran	Asia	2011	Sparrows	64	17
109	Khademvatan et al.	2013	Iran	Asia	2011	Starlings	39	5
110	Almeida et al.	2013	Brazil	South America	NS	Ostriches	46	8
110	Almeida et al.	2013	Brazil	South America	NS	Rheas	20	10
111	Chumpolbanchorn et al.	2013	Australia	Oceania	NS	Chickens	20	18
112	Cong et al.	2013	China	Asia	2011	Sparrows	313	39
113	El-Madawy and Metawea.	2013	Egypt	Africa	NS	Ostriches	120	16
114	Mohammed and Abdullah	2013	Iraq	Asia	2012	Chickens	65	39
115	Salant et al.	2013	Israel	Asia	NS	Crows	101	48
115	Salant et al.	2013	Israel	Asia	NS	Vultures	101	40
116	Puvanesuaran et al.	2013	Malaysia	Asia	NS	Ducks	205	30
117	Halova et al.	2013	Ireland	Europe	2007	Chickens	364	65
118	Akhtar et al.	2014	Pakistan	Asia	2011-2012	Chickens	300	109
119	Hamidnejat et al.	2014	Iran	Asia	NS	Chickens	106	55
120	Barros et al.	2014	Brazil	South America	2010-2011	Doves	206	12
121	Miao et al.	2014	China	Asia	NS	Gulls	659	139
122	Rong et al.	2014	China	Asia	2012-2014	Geese	600	102
123	Sarkari et al.	2014	Iran	Asia	2012	Turkeys	54	49
124	Ayinmode and Olaosebikan	2014	Nigeria	Africa	NS	Chickens	225	91
125	Mahmood et al.	2014	Pakistan	Asia	NS	Chickens	536	101
126	Wang et al.	2014	China	Asia	NS	Ducks	268	26
127	Vilares et al.	2014	Portugal	Europe	2009-2011	Pigeons	41	29
128	Elmore et al.	2014	Canada	North America	2011-2013	Geese	121	43
128	Elmore et al.	2015	Canada	North America	2011-2013	Geese	123	48
128	Elmore et al.	2015	Canada	North America	2011-2013	Geese	233	66
128	Elmore et al.	2015	Canada	North America	2011-2013	Geese	234	76
129	Zhao et al.	2015	China	Asia	2013	Ducks	1162	119
130	Camillo et al.	2015	Brazil	South America	2011	Chickens	137	102
131	Casartelli-Alves et al.	2015	Brazil	South America	2009-2011	Chickens	153	63
132	Chen et al.	2015	Taiwan	Asia	2013-2014	Pigeons	62	1
132	Chen et al.	2015	Taiwan	Asia	2013-2014	Owls	20	3
132	Chen et al.	2015	Taiwan	Asia	2013-2014	Owls	74	20
132	Chen et al.	2015	Taiwan	Asia	2013-2014	Magpies	22	10
133	Ma et al.	2015	China	Asia	2012	Chickens	1095	193
134	Zhang et al.	2015	China	Asia	2013	Ducks	50	11
135	Gebremedhin et al.	2015	Ethiopia	Africa	2012-2013	Chickens	601	183
136	Cano-Terriza et al.	2015	Spain	Europe	NS	Pigeons	142	11

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
137	Al-Adhami et al.	2016	Canada	North America	NS	Geese	71	2
138	Muhammad and Garedaghi	2016	Iran	Asia	2015	Chickens	100	`18
139	Abdoli et al.	2016	Iran	Asia	2013	Sparrows	200	17
140	Da Silva and Langoni	2016	Brazil	South America	NS	Ostriches	344	38
141	Cabezón et al.	2016	Spain	Europe	2009-2011	Gulls	479	109
141	Cabezón et al.	2016	Spain	Europe	2009-2011	Gulls	46	1
142	Feitosa et al.	2016	Brazil	South America	NS	Chickens	483	152
143	Feng et al.	2016	China	Asia	NS	Chickens	700	132
144	Fernandes et al.	2016	Brazil	South America	NS	Chickens	212	86
145	Gennari et al.	2016	Brazil	South America	NS	Penguins	100	28
146	Ibrahim et al.	2016	Egypt	Africa	2011	Chickens	304	34
147	Love et al.	2016	USA	North America	2012-2014	Hawks	71	22
147	Love et al.	2016	USA	North America	2012-2014	Owls	54	25
147	Love et al.	2016	USA	North America	2012-2014	Hawks	41	9
147	Love et al.	2016	USA	North America	2012-2014	Owls	28	13
147	Love et al.	2016	USA	North America	2012-2014	Hawks	20	6
148	Mose et al.	2016	Kenya	Africa	2014	Chickens	105	83
149	Sá et al	2016	Brazil	South America	NS	Turkeys	204	21
149	Sá et al	2016	Brazil	South America	NS	Chickens	322	83
150	Salant et al.	2016	Israel	Asia	2003	Chickens	157	18
150	Salant et al.	2016	Israel	Asia	NS	Turkeys	45	4
151	Salant et al.	2016	Israel	Asia	NS	Chickens	390	65
152	Tan et al.	2016	China	Asia	2013-2014	Geese	900	190
153	Verma et al.	2016	Canada	North America	2014-2015	Geese	169	12
154	Work et al.	2016	USA	North America	2011-2012	Geese	94	26
155	Pardini et al.	2016	Argentina	South America	NS	Chickens	33	10
156	Al-abodi	2017	Iraq	Asia	2016	Pigeons	80	11
157	Liu et al.	2017	China	Asia	2013-2014	Chickens	350	235
158	Ying et al.	2017	USA	North America	NS	Chickens	1185	230
159	Luo et al.	2017	China	Asia	NS	Chickens	571	72
160	Sa Silvio G. et al.	2017	Brazil	South America	NS	Chickens	629	176
161	Ayinmode et al.	2017	Nigeria	Africa	NS	Turkeys	320	13
162	Cong et al.	2017	China	Asia	2014-2015	Quails	390	25
163	Cong et al.	2017	China	Asia	2015	Quails	620	59
164	Elfadaly et al.	2017	Egypt	Africa	NS	Chickens	124	36
164	Elfadaly et al.	2017	Egypt	Africa	NS	Ducks	43	13
165	Gennari et al.	2017	Brazil	South America	2014	Vultures	121	16
166	Schares et al.	2017	Germany	Europe	NS	Chickens	470	55
167	Trevisani et al.	2017	Brazil	South America	NS	Chickens	133	84
168	Zou et al.	2017	China	Asia	2015-2016	Chickens	257	21
168	Zou et al.	2017	China	Asia	2015-2016	Ducks	115	9
168	Zou et al.	2017	China	Asia	2015-2016	Geese	42	2
169	Chikweto et al.	2017	India	Asia	NS	Chickens	145	39
170	Hamilton et al.	2017	India	Asia	2014	Chickens	81	26
171	Feng et al.	2017	China	Asia	2012-2015	Ostriches	315	20
172	Mahami-Oskouei, et al.	2017	Iran	Asia	2014	Chickens	50	4
173	Sukthana, et al.	2017	Thailand	Asia	2014-2015	Chickens	1200	304
174	Fathollahzadeh and Garedaghi	2017	Iran	Asia	2015	Chickens	150	33

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
175	Sivkova and Neprimerova.	2017	Russia	Europe	NS	Pigeons	28	10
176	Abdoli et al.	2018	Iran	Asia	NS	Crows	55	9
177	Karakavuk et al.	2018	Turkey	Asia	NS	Buzzards	25	23
178	Al-abodi et al.	2018	Iraq	Asia	NS	Pigeons	100	9
179	Al-doury et al.	2018	Iraq	Asia	2018	Chickens	264	176
180	Al Nasr et al.	2018	Saudi Arabia	Asia	NS	Chickens	244	29
181	Amouei et al.	2018	Iran	Asia	2014-2015	Chickens	243	127
181	Amouei et al.	2018	Iran	Asia	2014-2015	Ducks	87	40
181	Amouei et al.	2018	Iran	Asia	2014-2015	Ducks	20	9
181	Amouei et al.	2018	Iran	Asia	2014-2015	Ducks	20	12
182	Dwinata et al.	2018	Indonesia	Asia	NS	Ducks	188	47
183	Ferreira et al.	2018	Brazil	South America	2014	Chickens	58	30
184	Goncalves et al.	2018	Brazil	South America	NS	Chickens	417	157
185	Ibrahim et al.	2018	Egypt	Africa	2015	Pigeons	310	42
185	Ibrahim et al.	2018	Egypt	Africa	2015	Ducks	142	15
186	Lashari et al.	2018	Pakistan	Asia	2017	Chickens	71	19
187	Namroodi et al.	2018	Iran	Asia	2016-2018	Ducks	60	38
187	Namroodi et al.	2018	Iran	Asia	2016-2018	Buzzards	40	31
188	Nazir et al.	2018	Pakistan	Asia	NS	Pigeons	54	1
189	Pena et al.	2018	Brazil	South America	NS	Chickens	21	11
190	Acosta et al.	2018	Brazil	South America	2012-2015	Penguins	145	18
191	Skorpikova et al.	2018	Czech Republic	Europe	2015-2016	Ducks	280	15
191	Skorpikova et al.	2018	Czech Republic	Europe	2015-2016	Pheasants	350	11
192	Vieira et al.	2018	Brazil	South America	2011-2014	Chickens	386	64
193	Galal, et al	2019	Senegal	Africa	2016-2018	Chickens	1621	105
193	Galal, et al	2019	Senegal	Africa	2016-2018	Ducks	306	16
194	Cerqueira-Cézar et al.	2019	USA	North America	NS	Turkeys	20	6
195	Gallo et al.	2019	Brazil	South America	NS	Ostriches	20	16
195	Gallo et al.	2019	Brazil	South America	NS	Rheas	68	16
196	Nardoni et al.	2019	Italy	Europe	NS	Ducks	28	2
196	Nardoni et al.	2019	Italy	Europe	NS	Ducks	73	8
196	Nardoni et al.	2019	Italy	Europe	NS	Ducks	23	2
197	Huang et al.	2019	China	Asia	2014-2015	Sparrows	350	120
198	Bachand et al.	2019	Canada	North America	2015-2016	Geese	148	16
199	Hamilton et al.	2019	Antigua and Barbuda	North America	2016	Chickens	45	14
199	Hamilton et al.	2019	Dominica	North America	2016	Chickens	76	32
199	Hamilton et al.	2019	Trinidad	North America	2016	Chickens	41	12
200	Acosta et al.	2019	Chile	South America	2011-2015	Penguins	132	57
201	Al-Mayall et al.	2019	Iraq	Asia	2011-2013	Chickens	80	31
201	Al-Mayall et al.	2019	Iraq	Asia	2011-2013	Turkeys	80	28
201	Al-Mayall et al.	2019	Iraq	Asia	2011-2013	Geese	80	22
201	Al-Mayall et al.	2019	Iraq	Asia	2011-2013	Ducks	80	15
202	Andre et al.	2019	Brazil	South America	2010-2013	Geese	41	35
203	Hosseini et al.	2019	Iran	Asia	NS	Chickens	198	96
204	Sabri et al.	2019	Malaysia	Asia	NS	Chickens	50	10
205	Hind et al.	2019	Sudan	Africa	2015	Chickens	336	2
206	Konell et al.	2019	Brazil	South America	2017-2018	Geese	49	2
207	Liu et al.	2019	China	Asia	2017	Sparrows	131	11
208	Rodrigues et al.	2019	Portugal	Europe	NS	Chickens	348	10
209	Zhang et al.	2019	China	Asia	2015-2016	Pigeons	963	104
210	Mancianti et al.	2020	Italy	Europe	2012-2013	Crows	120	4
210	Mancianti et al.	2020	Italy	Europe	2012-2013	Magpies	651	41

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
211	dos Santos Silva et al.	2020	Brazil	South America	NS	Chickens	200	72
212	Braz et al.	2020	Brazil	South America	NS	Chickens	550	269
213	Song et al.	2020	China	Asia	NS	Chickens	107	7
214	Ahmed et al.	2020	Iraq	Asia	NS	Chickens	85	42
215	Aliyu et al.	2020	Nigeria	Africa	2015	Chickens	460	36
216	Alizadeh-Sarabi et al.	2020	Iran	Asia	NS	Chickens	97	21
217	Ammar et al.	2020	USA	North America	2016	Doves	186	2
218	Chaklu et al.	2020	Ethiopia	Africa	2018-2019	Chickens	384	278
219	Santos et al.	2020	Brazil	South America	NS	Sparrows	100	80
220	Issa et al.	2020	Iraq	Asia	2019-2020	Turkeys	26	15
220	Issa et al.	2020	Iraq	Asia	2019-2020	Chickens	21	17
220	Issa et al.	2020	Iraq	Asia	2019-2020	Geese	23	13
220	Issa et al.	2020	Iraq	Asia	2019-2020	Ducks	20	11
221	Li et al.	2020	China	Asia	NS	Chickens	377	30
221	Li et al.	2020	China	Asia	NS	Ducks	268	29
221	Li et al.	2020	China	Asia	NS	Geese	379	50
222	Nedisan et al.	2020	Romania	Europe	2018-2019	Chickens	789	319
222	Nedisan et al.	2020	Romania	Europe	2018-2019	Turkeys	30	8
222	Nedisan et al.	2020	Romania	Europe	2018-2019	Ducks	26	1
223	Tahri et al.	2020	Algeria	Africa	NS	Chickens	121	61
224	Khan et al.	2020	Pakistan	Asia	NS	Chickens	398	23
224	Khan et al.	2020	Pakistan	Asia	NS	Chickens	398	35
224	Khan et al.	2020	Pakistan	Asia	NS	Chickens	398	71
224	Khan et al.	2020	Pakistan	Asia	NS	Chickens	295	32
225	Sarr et al.	2020	Senegal	Africa	2018	Chickens	665	51
226	Iemmi et al.	2020	Italy	Europe	2016-2017	kestrel	238	62
227	Al-Dubbag et al.	2021	Iraq	Asia	2020	Chickens	91	16
228	Al-Hadad and Al-Rubaie	2021	Iraq	Asia	2019-2020	Chickens	100	11
229	Al-khanak and Salman	2021	Iraq	Asia	NS	Chickens	72	46
230	Ammar et al.	2021	USA	North America	NS	Vultures	104	4
231	Bartova et al.	2021	Czech Republic	Europe	2016-2018	Ostriches	409	149
232	Bata et al.	2021	Nigeria	Africa	2018-2019	Chickens	92	13
233	Dos Santos et al.	2021	Brazil	South America	2018-2019	Chickens	644	252
234	Lopes et al.	2021	Portugal	Europe	2019-2020	Buzzards	23	11
234	Lopes et al.	2021	Portugal	Europe	2019-2020	Vultures	21	3
234	Lopes et al.	2021	Portugal	Europe	2019-2020	Gulls	28	11
234	Lopes et al.	2021	Portugal	Europe	2019-2020	Gulls	23	10
234	Lopes et al.	2021	Portugal	Europe	2019-2020	White storks	35	11
235	Lv et al.	2021	China	Asia	2018-2020	Ducks	588	47
235	Lv et al.	2021	China	Asia	2018-2020	Chickens	1360	457
236	Nzelu et al.	2021	Nigeria	Africa	2016	Chickens	222	62
237	Nzelu et al.	2021	Nigeria	Africa	NS	Chickens	173	53
238	Thakur et al.	2021	India	Asia	NS	Chickens	522	34
239	Minutti et al.	2021	Brazil	South America	NS	Chickens	386	102
240	Lachkhem et al.	2021	Tunisia	Africa	2016-2018	Chickens	169	44
241	Rezende et al.	2021	Brazil	South America	NS	Chickens	50	48
242	Tayyub et al.	2022	Pakistan	Asia	2018	Pigeons	120	46
243	Karadjian et al.	2022	France	Europe	NS	Buzzards	41	21
243	Karadjian et al.	2022	France	Europe	NS	Owls	30	12
244	Zrelli et al.	2022	Tunisia	Africa	NS	Turkeys	35	7
244	Zrelli et al.	2022	Tunisia	Africa	NS	Chickens	105	21
245	Esmaeilifallah, et al.	2022	Iran	Asia	2014-2019	Pigeons	100	52
245	Esmaeilifallah, et al.	2022	Iran	Asia	2014-2019	Crows	100	34
246	Andreopoulou, et al.	2022	Greece	Europe	2016-2017	Chickens	934	88
247	Lamy and Kawan.	2022	Iraq	Asia	2021	Quails	150	29
248	Santos, et al.	2022	Brazil	South America	2015-2016	Ducks	67	39
249	Chen, et al.	2022	China	Asia	2015-2018	Chickens	1653	204

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Table 1 (*continued*)

Study No.	Author name	Publication years	Country	Continent	Time of sampling	Type of birds	Sample size	Positive
250	Aguilar-Marín, et al.	2022	Mexico	North America	NS	Chickens	150	101
251	Thuy and Inpankaew	2022	Thailand	Asia	2021	Ducks	217	68
252	Zanet et al.	2023	Italy	Europe	2017-2020	Owls	40	9
252	Zanet et al.	2023	Italy	Europe	2017-2020	Buzzards	26	10
252	Zanet et al.	2023	Italy	Europe	2017-2020	kestrel	20	5
253	Khordadmehr et al.	2023	Iran	Asia	2021	Pigeons	200	74
254	Chu et al.	2023	China	Asia	NS	Chickens	577	32
255	Baptista.	2023	Italy	Europe	2017-2020	Buzzards	26	10
255	Baptista.	2023	Italy	Europe	2017-2020	kestrel	20	5
256	Andreopoulou et al.	2023	Greece	Europe	2016-2017	Chickens	934	88
257	Khalife et al.	2023	Lebanon	Asia	2021-2022	Chickens	400	52
258	Ammar et al.	2024	USA	North America	2009-2019	Geese	26	9
258	Ammar et al.	2024	USA	North America	2009-2019	Ducks	202	38
258	Ammar et al.	2024	USA	North America	2009-2019	Gulls	23	18

Buzzards, Chickens, Crows, Doves, Ducks, Gulls, Hawks, Magpies, Ostriches, Owls, Penguins, Pheasants, Pigeons, Quails, Rheas, Sparrows, Starlings, kestrel, Turkeys, Vultures, Geese, and White storks.

annual precipitation, annual rainfall, average temperature, climate, humidity, total sample size, and number of positive samples (Tables 1 and 2).

2.3. Data synthesis and statistical analysis

For each included study, the point estimates and their respective 95% confidence intervals (CI) were calculated using the random-effects model. A meta-regression analysis was used to determine the possible association between average temperature, and year of publication with *T. gondii* prevalence in birds. Furthermore, Begg's funnel plot, Egger's funnel plot, and the Doi plot were implemented to investigate possible publication bias (Furuya-Kanamori and Others, 2021; Eslahi et al., 2023a; Eslahi et al., 2023b). The prevalence data were pooled through statistical meta-analysis with the Freeman-Tukey double arcsine method for the random-effects model, based on the inverse variance approach for measuring weight.

In order to visualize possible heterogeneity among the included studies, a forest plot analysis was used. The heterogeneity index among the included studies was defined using the I^2 index and Cochrane's Q test, so that I^2 values of < 25%, 25–75%, and > 75% were considered to have low, moderate, and high heterogeneity, respectively. A p-value < 0.05 was regarded as statistically significant. All analyses were conducted by the meta-package in R (version 3.6.1) (Team, 2020).

3. Results

3.1. Literature search selection and data extraction

The findings from the search and study selection process are outlined in a PRISMA flow diagram (Fig. 1). Initially, a total of 2,859 records were identified. Following the removal of duplicates and non-eligible studies, 258 articles containing 380 datasets and 90,480 bird samples met the inclusion criteria.

Our analysis encompassed 17,269 infected birds from six continents, spanning 64 countries. Specifically, there were 149 studies from Asia, 85 from Europe, 60 from South America, 44 from North America, 40 from Africa, and 2 from Oceania.

Brazil had the highest number of studies (50), followed by China (42) (Supplementary Fig. 1). The estimated global prevalence of *T. gondii* in birds was determined to be 24% (21 - 26%) (Supplementary Fig. 1).

Based on the included studies, a map illustrating the prevalence of *T. gondii* in birds across various global regions was generated using QGIS3 software (https://qgis.org/en/site/). Additionally, a Sankey plot indicated that the largest number of studies originated from Asia (Fig. 2A-B).

3.2. Pooled prevalence based on source of samples, and diagnostic methods

The pooled prevalence rates varied depending on the type of samples collected. For serum samples, the estimated prevalence was 25% (23 - 28%) and for tissue samples this rate was 15% (11 - 20%) (Table 2).

Regarding detection method, the pooled prevalence ranged between 39-1%. Accordingly, the highest estimated rate (39%, 30 - 48%) was related to latex agglutination test (LA).

In addition, the pooled prevalence was as follows for different diagnostic techniques; 30% (23 - 38%) for indirect immunofluorescence assay (IFA), 27% (16 - 39%) for indirect hemagglutination test (IHA), 25% (22 - 29%) for modified agglutination test (MAT),

Table 2
Sub-group analysis based on annual precipitation, humidity, annual rainfall, average temperature, climate, continent, wild vs. domestic birds, bird type, sample type, and diagnostic method in included studies.

Variables	No studies	Sample size	Positive	Pooled prevalence (95% CI)	Heterogeneity		
					I^2	τ^2	p-value
Annual precipitation							
<300	199	54881	8373	18 %(16%-21%)	97	0.060	<0.001
300-650	131	27176	6593	32% (27-36%)	98	0.069	<0.001
651-1000	34	4131	917	22% (16-28%)	93	0.039	<0.001
>1000	16	4292	1386	30% (20-42%)	98	0.056	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Humidity (%)							
<40	35	4545	1113	28% (20-36%)	96	0.067	<0.001
40-75	272	62143	13030	24% (22-27%)	97	0.065	<0.001
>75	73	23792	3126	18% (14-23%)	98	0.067	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Annual rainfall (mm)							
<400	84	14090	3282	30% (25-35%)	97	0.063	<0.001
401-1000	168	52731	7694	17% (15-21%)	98	0.061	<0.001
1001-1500	110	20614	5687	29% (24-33%)	97	0.065	<0.001
>1500	18	3045	652	23% (14-32%)	96	0.045	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Average temperature (°C)							
<10	42	13818	1308	13% (7-18%)	98	0.046	<0.001
10-20	192	46918	8394	22% (19-25%)	97	0.064	<0.001
>20	146	29744	7549	30% (26-34%)	97	0.065	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Climate							
Subtropical highland oceanic climate	7	1583	268	27% (6-55%)	99	0.145	<0.001
Cold semi-arid climates	33	3965	1082	30% (22-38%)	96	0.062	<0.001
Humid subtropical climate	20	3812	635	18% (12-26%)	93	0.034	<0.001
Hot-summer Mediterranean climate	54	9821	1435	22% (17-28%)	96	0.053	<0.001
Tropical monsoon climate	1	41	12	30% (18-44%)	NA	NA	NA
Tropical rainforest climate	3	261	129	50% (35-66%)	84	0.015	0.002
Tropical wet climate	12	3369	1055	30% (24-39%)	95	0.017	<0.001
Hot desert climate	39	5112	1647	35% (28-43%)	97	0.061	<0.001
Hot semi-arid climates	11	4416	529	18% (9-30%)	97	0.050	<0.001
Marine climate	22	9398	525	7% (3-12%)	98	0.035	<0.001
Tropical savanna climate	70	11824	3729	34% (27-40%)	97	0.084	<0.001
Oceanic climate	13	3368	986	28% (14-45%)	98	0.098	<0.001
Hot humid continental climate	94	32531	5106	16% (13-19%)	97	0.041	<0.001
Total	378	89501	17138	24% (21-26%)	98	0.066	<0.001
Continent							
Africa	40	8854	1968	26% (19-33%)	98	0.060	<0.001
Asia	149	37757	7209	22% (19-23%)	97	0.058	<0.001
Europe	85	25523	3055	16% (12-20%)	98	0.054	<0.001
North America	44	7487	1443	23% (17-30%)	97	0.065	<0.001
Oceania	2	850	320	64% (12-100%)	96	0.152	<0.001
South America	60	10009	3274	37% (300-43%)	97	0.074	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Diagnostic method							
Bioassay	16	5793	261	9% (3 - 17%)	97	0.050	<0.001
Direct agglutination test (DAT)	10	3448	227	9% (4 - 17%)	96	0.029	<0.001
Enzyme-linked immunosorbent assay (ELISA)	37	14463	2542	18% (14-23%)	97	0.027	<0.001
Indirect hemagglutination test (IHA)	18	7258	1594	27% (16-39%)	98	0.078	<0.001
Indirect Immunofluorescence Assay (IFA)	41	9575	2765	30% (23-38%)	97	0.065	<0.001
Modified agglutination test culture (MAT)	180	35587	6959	25% (22-29%)	97	0.061	<0.001
Polymerase chain reaction (PCR)	48	7548	1088	18% (13 - 24%)	95	0.061	<0.001
Sabin Feldman Dye Test (SFDT)	6	2252	19	1% (0- 5%)	84	0.013	<0.001
Latex agglutination test (LA)	31	5100	1770	39% (30 - 48%)	98	0.064	<0.001

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Table 2 (*continued*)

Variables	No studies	Sample size	Positive	Pooled prevalence (95% CI)	Heterogeneity		
					I^2	τ^2	p-value
Total	387	91024	17225	24% (21-26%)	97	0.064	<0.001
Sample type							
Serum	324	78955	16081	25% (23-28%)	97	0.063	<0.001
Tissues	60	12721	1277	15% (11-20%)	97	0.064	<0.001
Total	384	91676	17358	24% (21-26%)	97	0.065	<0.001
Wild vs. domestic birds							
Wild bird	157	27665	3771	18% (15-21%)	96	0.062	<0.001
Domestic bird	223	62815	13480	28% (25 - 31%)	98	0.064	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001
Bird type							
Buzzards	9	426	183	52% (34-70%)	94	0.068	<0.001
Chickens	157	45111	10645	30% (26-34%)	98	0.064	<0.001
Crows	7	1109	277	25% (7-49%)	98	0.111	<0.001
Doves	6	708	26	3% (1-6%)	42	0.002	0.12
Ducks	43	9726	1197	19% (15-25%)	94	0.041	<0.001
Geese	32	6374	1199	19% (14-25%)	93	0.039	<0.001
Gulls	7	1319	298	28% (12-49%)	90	0.071	<0.001
Hawks	6	251	63	25% (15-36%)	67	0.014	0.009
Magpies	3	706	56	19% (2-0.44%)	91	0.052	<0.001
Ostriches	10	2589	328	18% (0.066-0.346)	97	0.081	<0.001
Owls	10	743	221	29% (18-42%)	94	0.038	<0.001
Penguins	4	675	110	18% (4-40%)	97	0.056	<0.001
Pheasants	3	1038	27	2% (1-4%)	11	0.002	0.76
Pigeons	29	8522	800	12% (6-18%)	97	0.064	<0.001
Quails	5	1736	225	12% (5-21%)	96	0.019	<0.001
Rheas	3	157	29	22% (2-52%)	91	0.068	<0.001
Sparrows	15	4300	443	14% (5-.26%)	98	0.083	<0.001
Starlings	3	135	10	8% (0-19%)	76	0.015	0.01
Turkeys	15	3362	774	31% (17-46%)	97	0.085	<0.001
Vultures	7	867	231	18% (5-34%)	97	0.063	<0.001
White storks	3	348	37	15% (4-31%)	86	0.022	<0.001
Kestrel	3	278	72	25% (20-30%)	61	0.012	<0.001
Total	380	90480	17269	24% (21-26%)	98	0.066	<0.001

18% (14 - 23%) for enzyme-linked immunosorbent assay (ELISA), 18% (13 - 24%) for molecular test, 9% (4 - 17%) for direct agglutination test (DAT), 9% (3 - 17%) for studies using bioassay, and 1% (0 - 5%) for studies using Sabin Feldman dye test (SFDT) (Table 2).

3.3. Pooled prevalence based on wild/domestic status, and type of birds

In terms of wild/domestic status, the pooled prevalence was notably higher in domestic birds, reaching 28% (25- 31%) compared to wild birds (Table 2).

Among different types of birds, buzzards exhibited the highest prevalence reaching 52% (34 - 70%).

Furthermore, the pooled prevalence in bird hosts was as follows: 31% (17 - 46%) in turkeys, 30% (26 - 34%) in chickens, 29% (18 - 42%) in owls, 29% (12 - 49%) in gulls, 25% (20 - 30%) in Kestrel, 25% (15 - 36%) in hawks, 25% (7 - 49%) in crows, 22% (2 - 52%) in rheas, 19% (15 - 25%) in ducks, 19% (14 -25%) in geese, 19% (6 - 34%) in ostriches, 19% (2 - 44%) in magpies, 18% (6 - 34%) in vultures, 18% (4 - 40%) in penguins, 15% (4 - 31%) in white storks, 14% (5 - 26%) in sparrows, 12% (6 -18%) in pigeons, 12% (5 - 21%) in quails, 8% (0 - 19%) in starlings, 3% (1 - 5%) in doves, and 2% (1 - 4%) in pheasants (Table 2).

3.4. Pooled prevalence based on continent and country

The pooled prevalence estimates varied across continents, ranging from 16-64%. Accordingly, Oceania had the highest prevalence (64%, 12 - 100%), while Europe displayed the lowest prevalence rate (16%, 12 - 20%) (Table 2).

Analysis at the country level revealed that Nicaragua, despite having only one study available, had the highest pooled prevalence (86%, 77 - 91%) (Supplementary Fig. 2).

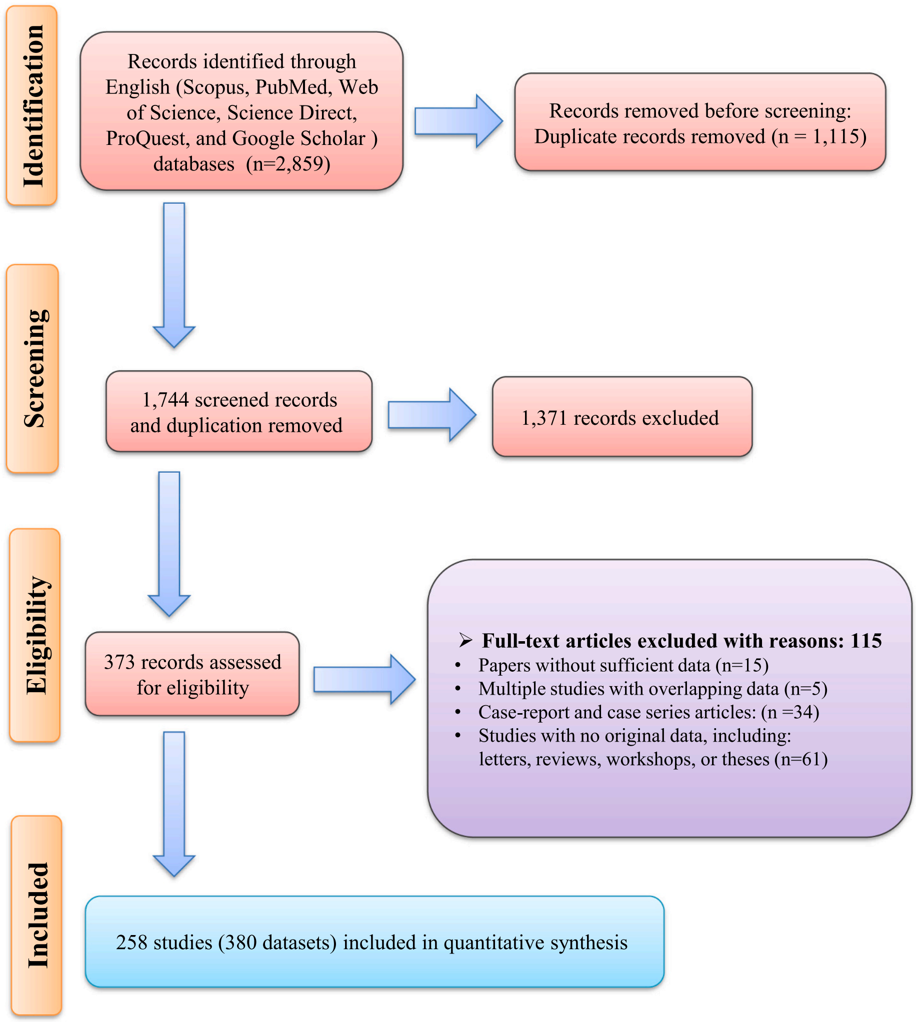

Fig. 1. Flow diagram of the study design process.

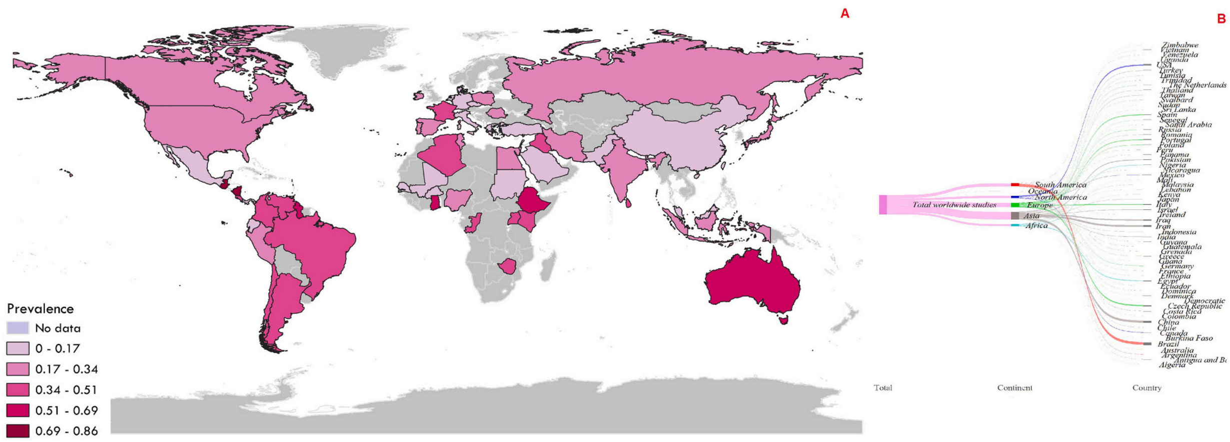

Fig. 2. The global prevalence of *Toxoplasma gondii* in birds in different geographical regions of the world based on included studies.

3.5. Pooled prevalence based on climate variables

The highest pooled prevalence was associated with regions characterized by an average temperature > 20°C, annual precipitation of 300-650 mm, annual rainfall of < 400 mm, and humidity of < 40% with estimates of 30% (26 - 34%), 32% (27 - 36%), 30% (25 - 35%), and 28% (20 - 36%), respectively (Table 2).

Regarding different climatic variables, the highest prevalence rate (50%, 35 - 66%) was found in regions with tropical rainforest climate and the lowest prevalence rate (7%, 4 - 12%) was associated with marine climate (Table 2).

3.6. Meta regression

The meta-regression analysis revealed that among the examined factors, both average temperature and year of publication were significant in explaining the estimated heterogeneity, with statistically significant results for all criteria. Accordingly, the following report was observed for each factor: 1) average temperature (slope = 0.2983, $p < 0.0001$), and 2) year of publication (slope = 9.100, $p < 0.004$) (Fig. 3A-B).

3.7. Publication bias

A highly significant publication bias was observed using both Egger's test (t = 4.71, $p < 0.0001$) and Begg's test (t = 7.70, $p < 0.0001$) (Fig. 4A & B). Furthermore, Doi plot analysis showed a major asymmetry (LFK index: 2.71) (Fig. 4C).

4. Discussion

Toxoplasma gondii infection has a significant impact on public health as well as animal health, welfare and production globally. It is widely distributed and is highly prevalent in many areas of the world, leading to high costs to society, and serious outcomes in both humans and animals populations (Cabezon et al., 2011; Omonijo et al., 2022).

Several factors account for the variations in infection rates observed across different geographical regions, with particular emphasis on the effectiveness of infectious disease control measures, the sensitivity of employed methods, and the specific geographic locations where birds were discovered. Herein, the elevated prevalence of *T. gondii* in birds observed in Oceania with a high abundance of avian populations (Dubey et al., 2005), underscores the need for additional research.

Warmer climate provide favorable circumstances for the survival of the oocysts in the environment (Galeh et al., 2020; Siqueira et al., 2013). Similarly, our analysis revealed that the highest prevalence rate was associated with average temperature higher than 20°C. Moreover, a significant heterogeneity in the prevalence of *T. gondii* was detected regarding climate and geographic factors.

A broad spectrum of diagnostic tests was utilized in the studies we included. However, LA found to has the highest prevalence rate. It is expected that different detection techniques yield heterogeneous data. In this regard, the diagnostic performance of the MAT has been reported to be applicable for many host species and more accurate, compared to the ELISA (Omonijo et al., 2022). Serological assays have different sensitivity and specificity, although they remain the primary screening method for qualitatively detecting

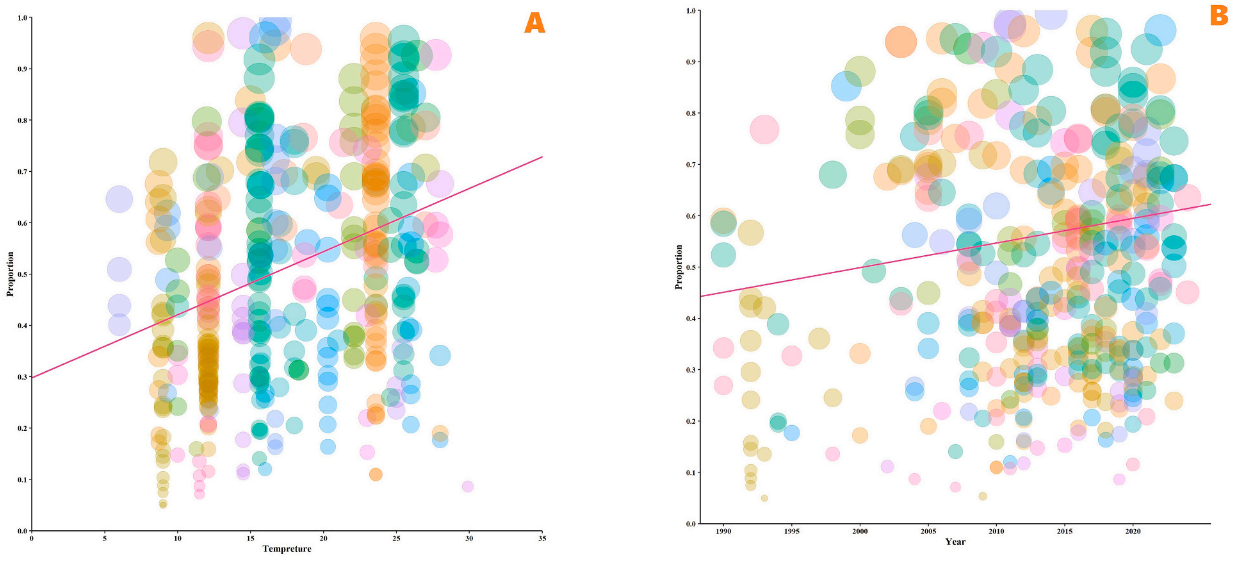

Fig. 3. A meta-regression graph representing the global prevalence of *Toxoplasma gondii* in birds based on (A) average temperature and, (B) year of publication (The pink line is the regression line, which was plotted based on the intercept and the slope of the regression model. The different color bubbles represent the countries under study and their sizes indicate the effect size of each study).

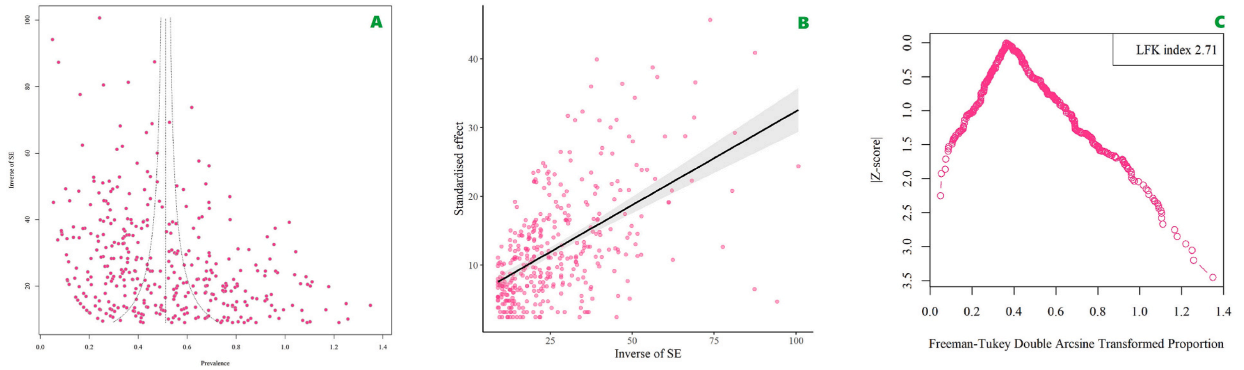

Fig. 4. (A) Egger's funnel plot, and (B) Begg's plot to assess publication bias in studies evaluating *Toxoplasma gondii* in birds (colored circles represent each study and the middle line is the effect size and the other two lines arc the corresponding confidence ranges. (C) Doi plot for the global prevalence of *T. gondii* in birds (a Luis Furuya -Kanamori (LFK) index 2.71 indicates major asymmetry).

antibodies against *T. gondii* infection (Omonijo et al., 2022). PCR-based techniques may have high sensitivity and specificity. However, these tools possess different disadvantages such as relatively high cost. The use of bioassay has become less common, while direct isolation of the parasites to cell cultures is being discussed more (Opsteegh et al., 2020). Direct microscopic method is not an appropriate and reliable test to detect *T. gondii* because of low sensitivity and requirement of expertise, knowledge and skills (Khademvatan et al., 2017; Saki and Khademvatan, 2014).

Birds are susceptible to *T. gondii* with tissue cysts capable of persisting in their body, presenting a potential source of infection for other hosts (Cabezon et al., 2011; Foroutan et al., 2019). Findings of the present study suggests that the prevalence of *T. gondii* was high in several orders of birds, such as Galliformes, Accipitriformes, Passeriformes, and Anseriformes. However, the highest prevalence rate was noted in carnivorous birds. These birds are at the top of the food pyramid, so the burden of pollution, including with biological agents, that can accumulate in food chains, is high in them (Fath and Killian, 2007).

Carnivorous birds are thought to acquire *T. gondii* infection through ingestion of tissue cysts present in the tissues of infected prey; nevertheless, they can also become infected from sporulated oocysts, e.g. by ingesting contaminated water or feed (Dubey et al., 2010). The buzzard (*Buteo buteo*) is a carnivore and predator living in a variety of climates, from the watery desert to the North Pole (Martin et al., 2014; Yosef et al., 2019). The reason for the high prevalence in this bird is likely attributed to its feeding habit and the widespread distribution, making it a valuable indicator host across different countries. Significantly, turkeys exhibited a relatively high prevalence of *T. gondii* infection. The importance of the infection in turkey, as ground-feeding bird, lies in its potential role as indicator of environmental contamination. Additionally, free-ranging chickens and other ground-feeding birds serve as effective sentinels or indicators of environmental contamination with *T. gondii* oocysts. (Dubey et al., 2020).

Toxoplasma gondii strains isolated from birds can reflect the various genotypes present in the environment as well as in their primary predators and prey. A comprehensive analysis of the genetic diversity of *T. gondii* isolates from birds revealed that atypical genotypes were the most prevalent (59%). Types II, III, and I were less common, with prevalence rates of 23.4%, 13.8%, and 2%, respectively. Moreover, the review demonstrated the significant genetic diversity of *T. gondii*, with non-clonal strains circulating in birds across South and North America, while clonal parasites with limited genetic variation were predominant in Europe, Asia, and Africa (Galeh et al., 2023).

The present systematic review and meta-analysis had some strengths including the comprehensive literature search in four international databases, the large sample size of birds included, analysis of several subgroups, and the rigorous methodology. However, the current review has also some limitations, including lack of data regarding the prevalence of *T. gondii* infection among birds from many countries, limited sample sizes in some reports, lack of evaluation of related risk factors in many studies, variation in sensitivity and specificity of diagnostic tests, and language limitations. Given these limitations, it is important to note that our findings may not precisely reflect the prevalence rate, although, it is very useful as it gives an overview of prevalence of *T. gondii* in birds at a global scale.

5. Conclusion

Studying epidemiology of *T. gondii* in birds provides valuable information for health policy makers to assess the current status of the infection and it helps to evaluate, and possibly mitigate potential threats to the poultry industry, wild bird populations, domestic and wild mammals, and humans. The current study sheds light on widespread distribution of *T. gondii* throughout continents and countries, with varied prevalence rates determined by factors such as climate, geographical location, and bird species. The prevalence rates varied depending on the sample sources and diagnostic procedures used, emphasizing the significance of standardized test techniques. Carnivorous birds of prey identified as prominent hosts, demonstrating their involvement in *T. gondii* transmission dynamics. The genetic diversity of *T. gondii* strains in birds demonstrates the complicated nature of transmission mechanisms.

Future study should focus on filling information gaps about *T. gondii* prevalence in bird populations globally. Standardization of surveillance techniques and diagnostic methods may improve our understanding of the parasite's distribution and transmission dynamics in bird species. Furthermore, specific measures, such as raising awareness among poultry producers and implementing steps to prevent environmental contamination, are critical for minimizing *T. gondii*'s impact on both animal welfare and public health.

Finally, this study is a critical step in improving our understanding of *T. gondii* epidemiology in birds and emphasizes the need of collaborative efforts in combating this ubiquitous parasite infection. By prioritizing multidisciplinary research and implementing preventative measures, we may reduce the worldwide burden of *T. gondii* while also protecting the health of humans and animals.

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Ethical considerations

Ethical approval was required and provided for this study, as stated by our institutional review board.

Declaration of competing interest

The authors declared no potential conflicts of interest concerning the research or authorship.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.parepi.2024.e00350.

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