15 When *Vibrios* Take Flight: A Meta-Analysis of Pathogenic *Vibrio* Species in Wild and Domestic Birds

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Abstract

Of the over 100 species in the genus *Vibrio*, approximately twelve are associated with clinical disease, such as cholera and vibriosis. Crucially, eleven of those twelve, including *Vibrio cholerae* and *Vibrio vulnificus*, have been isolated from birds. Since 1965, pathogenic *Vibrio* species have been consistently isolated from aquatic and ground-foraging bird species, which has implications for public health, as well as the One Health paradigm defined as an ecology-inspired, integrative framework for the study of health and disease, inclusive of environmental, human, and animal health. In this meta-analysis, we identified 76 studies from the primary literature which report on or examine birds as hosts for pathogenic *Vibrio* species. We found that the burden of disease in birds was most commonly associated with *V. cholerae*, followed by *V. metschnikovii* and *V. parahaemolyticus*. Meta-analysis wide prevalence of our *Vibrio* pathogens varied from 19% for *V. parahaemolyticus* to 1% for *V. mimicus*. Wild and domestic birds were both affected, which may have implications for conservation, as well as agriculturally associated avian species. As pathogenic *Vibrios* become more abundant throughout the world as a result of warming estuaries and oceans, susceptible avian species should be continually monitored as potential reservoirs for these pathogens.

Keywords

Vibrio spp. · Wild birds · Disease · Pathogenic · Ecology

15.1 Introduction

Waterborne pathogens around the globe are experiencing a period of unprecedented global change, with the Vibrionaceae categorized among the most climate-sensitive families of aquatic prokaryotes (Hofstra 2011; Lipp et al. 2002). Evidence continues to mount concerning the uptick in the abundance, distribution, and phenology of the Vibrionaceae, since rising temperatures, humidity, and precipitation have led to their increased survival and rates of replication (Wittman and Flick 1995; Montánchez and Kaberdin 2020; Vezzulli et al. 2020). Within this family resides the genus *Vibrio*, a genetically diverse group of gram-negative, motile, and facultatively anaerobic bacteria that are endemic to marine and estuarine waters (Pruzzo et al. 2005). With over 100 named species in the *Vibrio* genus,

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approximately twelve are known to be pathogenic to human hosts (Huehn et al. 2014). Specifically, eleven of the twelve, i.e., *V. alginolyticus*, *V. cholerae*, *V. cincinnatiensis*, *V. hollisae*, e.g., *Grimontia hollisae*, *V. furnissii*, *V. mimicus*, *V. parahaemolyticus*, *V. vulnificus*, *V. harveyi*, *V. scophthalmi,* and *V. metschnikovii,* are the causative agents of human vibriosis, a term that incorporates a broad range of clinical signs (Ramamurthy et al. 2014; Igbinosa and Okoh 2008; Morris and Acheson 2003). These pathogenic species arguably include some of the greatest public health burdens worldwide, and over the last 40 years, the incidence of *Vibrio* infections has strikingly increased (Rodrick 1991; Baker-Austin et al. 2010, 2017). The continued rise of the incidence and prevalence of *Vibrio* pathogens has contributed to an unprecedented worldwide health burden of enteric, diarrheal diseases (Levy et al. 2018; Semenza 2020). Yet, the Vibrionaceae are not only expanding their breadth throughout the human population—over the last one hundred and fifty years, but it also appears that the *Vibrio* genus is expanding its niche into avian hosts, with ensuing implications for the One Health paradigm, and how we contextualize "human" diseases (Sekyere et al. 2020; Destoumieux-Garzón et al. 2018; Jeamsripong et al. 2020; Sweet et al. 2021).

During the fifth pandemic of cholera (1881–1886), the bacteriologist Gamelaia reported a disease afflicting Rock Pigeons (*Columba livia*) and domestic chickens (*Gallus gallus*) in southern Russia. It was described as "a disease of fowls," of which the etiological agent was indistinguishable by morphological examination from *Vibrio cholerae* (Gamaleia 1888; Henze 2010). This etiological agent would eventually be classified as *Vibrio metschnikovii*, and by the early twenty-first century, it would be considered one of the twelve pathogenic *Vibrio* species that cause disease in human hosts (Huehn et al. 2014; Skerman et al. 1980; Tantillo et al. 2004). The occurrence of another pathogenic *Vibrio* isolated from birds would not be reported until 1966, when individual species from the Gifu and Higashiyama Zoos (Table 15.2) in Japan tested positive by culture for Biotypes 1 and 2 of *Vibrio parahaemolyticus* (Ose 1967). Pathogenesis in these zoo birds was not reported (Ose 1967). Based on the literature, it is possible that the bird that had cultured positive for Biotype 2 of *Vibrio parahaemolyticus* was in fact shedding *V. alginolyticus* (Sakazaki 1968; Fu et al. 2016).

Pathogenic *Vibrio* species can be lethal in human hosts. For example, *Vibrio vulnificus* is a causative agent of primary septicemia with a case fatality rate of up to fifty percent (Bross et al. 2007; Oliver et al. 2012). As one of the world's leading causes of seafood-related deaths, *Vibrio vulnificus* is an opportunistic pathogen which causes high morbidity and mortality among the immunocompromised and those with liver disease (Oliver and Sadowsky 2015; López-Pérez et al. 2021). *Vibrio cholerae*, specifically serotypes O1 and O139, is likely the most well-known member of the *Vibrio* genus. It is a pathogen which has generated seven pandemics since 1817, and whose ecology and pathogenesis has been covered in depth (Hu et al. 2016; Mutreja et al. 2011; Colwell 1996; Colwell and Spira 1992; Faruque et al. 2003; Almagro-Moreno and Taylor 2014). *Vibrio parahaemolyticus* is a leading cause of seafood-borne illness, with clinicians reporting gastroenteritis and septicemia as the primary causes of morbidity among patients (Li et al. 2019; Letchumanan et al. 2014). *V. alginolyticus* and *V. fluvialis* are considered emerging pathogens and have been linked to gastroenteritis and extraintestinal infections (Ramamurthy et al. 2014; Mustapha et al. 2013). The remaining *Vibrio* species, *V. cincinnatiensis*, *V. hollisae*, e.g., *Grimontia hollisae*, *V. furnissii*, *V. mimicus*, *V. harveyi*, *V. scophthalmi,* and *V. metschnikovii* have been linked to sporadic reports of disease in human hosts (Magalhães et al. 1996; Jean-Jacques et al. 1981; Jäckel et al. 2020; Edouard et al. 2009; Derber et al. 2011; Kay et al. 2012), however, that does not diminish their clinical, veterinary, or ecological importance.

The One Health paradigm is a collaborative endeavor that seeks to incorporate the health of the environment, animals, and humans, given the understanding that the resilience of these individual components is integrated and intertwined (Patz and Hahn 2013; Conrad et al. 2009). Thus, the emergence of pathogenic *Vibrio* species in birds is not only of public health importance (Islam et al. 2020; Laviad-Shitrit et al. 2017), but also of significance to avian disease ecology, as little is known of the large-scale effects that members of the *Vibrio* genus may have upon species of conservation concern (Friend 2006; Friend et al. 2001). With few exceptions (Almagro-Moreno and Taylor 2014), little is also known concerning the role that birds may play in the maintenance or potentially cyclical contamination of the brackish, aquatic reservoirs they share with other susceptible vertebrates (Fukushima and Seki 2004; Ogg et al. 1989; West et al. 1983; Vezzulli et al. 2010; Meszaros et al. 2020). Therefore, in this chapter, we build on the work of prior investigators who have identified the presence of pathogenic *Vibrio* species in avian species to a) identify the avian taxas most likely to excrete the pathogens and b) assess the prevalence of individuals in each community or sample that do so. We further examine whether pathogenic *Vibrio* species are immunogenic and/or pathogenic to birds and the duration that they shed in experimental infection studies. We focus not just on studies that have identified the presence or absence of pathogenic *Vibrio* species in wild avian communities, but also include experimental infection and immunity studies. Our objective is to provide a baseline framework by which avian disease ecologists, wildlife management professionals, veterinarians, and One Health personnel can evaluate and/or mitigate the potential risks of emerging pathogenic *Vibrio* species within our wild birds.

15.2 Methods

Using Google Scholar and Web of Science (Wiethoelter et al. 2015; Murray et al. 2016), we searched for peer-reviewed studies, pre-prints, abstracts, and graduate theses in which the antibodies against or the antigens of pathogenic *Vibrio* species were isolated from birds or from the avian environment (e.g., the isolation of *Vibrio* pathogens from avian fecal matter or their nests) (Ayala et al. 2020). In our search strategy, we used the following search terms and Boolean operators: "*Vibrio* pathogen of interest" OR "*Vibrio* pathogen and disease" and "bird*" OR "wild bird*" OR "avian" ($n = 14{,}950$). In our search, we systematically searched for studies that examined evidence of infection by the following members of the *Vibrio* genus: *V. alginolyticus, V. cholerae, V. cincinnatiensis, V. furnissii, V. mimicus, V. parahaemolyticus, V. vulnificus, V. harveyi, V. scophthalmi,* and *V. metschnikovii.* Given the relatively recent taxonomic reclassifications of *Grimontia hollisae* (Thompson et al. 2003) and *Photobacterium damselae* (Smith et al. 1991) from the genus *Vibrio*, we also included these pathogens in our analysis. We included experimental infection studies, case reports, and cross-sectional studies published between 1966 and January 1, 2022. In our analysis, we excluded sources that did not serve as primary literature involving investigations of pathogenic *Vibrio* infections in domestic or wild birds, e.g., retrospective studies and review papers (retrospective and review papers, $n = 24$) as well as duplicates (duplicates, $n = 81$). We also excluded any literature without a clear diagnostic and physiological association between domestic or wild birds as hosts of our *Vibrio* species of interest (exclusion criteria, $n = 14{,}845$).

From each study, we extracted the following elements when available: avian species or taxonomic grouping, *Vibrio* species, country, year the study was conducted or published, the number of birds tested or infected, the number of birds from which *Vibrio* was isolated, and the method(s) by which pathogenic *Vibrio* species were identified. Where possible, we identified the prevalence of our *Vibrio* pathogens of interest, including presence and absence, to determine study-wide prevalence. We also reported serotypes and/or clinically important strains when that information was provided. We further identified whether our *Vibrio* pathogens of interest were associated with clinical signs or avian mortality events, however, unless specifically stated in the text, we could not determine whether our *Vibrio* pathogens of interest were the causative agent(s) of reported morbidity or mortality.

15.3 Results

15.3.1 Literature Review

We identified 76 studies from the primary literature that met our inclusion criteria, resulting in 425 study records of avian species or taxonomic groups from which the presence or absence of pathogenic *Vibrio* species was recorded (identified species, $n = 171$, identified families, $n = 46$). In our meta-analysis, a study record ranges from a single examined bird to 565 examined birds, which reflects the same species or taxonomic group that was tested for a single pathogenic *Vibrio* species of interest that originated from within the same study (Tables 15.1, 15.2, 15.3, 15.4, and 15.5). In our meta-analysis, 29 countries were represented, constituting all continents except for Antarctica. Of the fifty-five years between 1966 and the start of 2022, studies were either published in or conducted in 41 of them. Sixteen study records did not provide sufficient information from which to identify *Vibrio* prevalence, as either the number of birds, flocks, nests, or sites were incompletely reported or collected samples were pooled. When the *Vibrio* pathogens of interest were either not named or not classified into species, it was categorized as "*Vibrio* spp.".

15.3.2 *Vibrio cholerae*

A total of 41 studies in the primary literature examined the role of *Vibrio cholerae* in wild or domestic birds (Laviad-Shitrit et al. 2017; Ogg et al. 1989; Aberkane et al. 2015; Aguirre et al. 1991, 1992; Akond et al. 2008; Bisgaard and Kristensen 1975; Bisgaard et al. 1978; Bogomolni et al. 2008; Buck 1990; Cardoso et al. 2014, 2018; Contreras-Rodríguez et al. 2019; Cox 1992; Fernández-Delgado et al. 2016; Hirsch et al. 2020; Ismail et al. 2021; Metzner et al. 2004; Laviad-Shitrit et al. 2018; Lee et al. 1982; Huamanchumo 2021; Mehmke et al. 1992; Myatt and Davis 1989; Páll et al. 2021; Rodríguez et al. 2010; Roges et al. 2010; Sack 1973; Salles et al. 1976; Sanyal et al. 1974; Schlater et al. 1981; Siembieda et al. 2011; Singh et al. 1975; Song et al. 1998; Strauch et al. 2020; Szeness et al. 1979; Watanabe et al. 2002; Watts et al. 1993; Sakazaki and Shimada 1977; Wobeser and Rainnie 1987; Zhang et al. 1996; Zheng et al. 2020, 2021). One hundred and fifty-six study records investigated the presence or absence of *Vibrio cholerae,* with the most common technique utilized being culture alone, followed by culture and PCR, or PCR coupled with sequencing. Twenty-five study records reported multiple serotypes from the same species, in the same study. Five of those 25 study records dealt with individual birds who either excreted or displayed multiple serotypes within the same fecal or blood sample or were sampled longitudinally and subsequently cultured positive for different serotypes at different times (Ogg et al. 1989; Singh et al. 1975). Four study records reported the detection of *Vibrio cholerae* O1 from within one or a flock of birds, with Inaba and Ogawa each reported at least once (Ogg et al. 1989; Rodríguez et al. 2010; Salles et al. 1976; Sanyal et al. 1974). Serotype distribution across species or taxonomic groups was not analyzed, since the number of birds positive for each serotype was usually not provided in the primary literature. We do, however, report the available data in Table 15.1. The most common "type" of *Vibrio cholerae* reported from birds was non-O1/O139, however, many study records did not identify or report the serotype of *Vibrio cholerae* that was isolated. *Vibrio cholerae* O139 was not reported from any study.

One hundred and seven ($n = 107$) species were examined for the presence of *Vibrio cholerae* antigens or antibodies. An additional sixteen records were extracted from the literature, but we were not able to identify those study records to species. The Anatidae (waterfowl) represented 49 study records, Laridae (gulls and terns) represented 20 study records, and the Ardeidae (shorebirds) represented 10 study records. Within our meta-analysis, 5492 reported

Table 15.1 This table details the study records extracted from the 41 studies that investigated birds as hosts for Vibrio cholerae, both O1 El tor and Non-O1. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for Vibrio cholerae, the total number of birds examined for V. cholerae, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column. For serotypes or strains, there were several primary categories, for Non-O1, this involves any Vibrio cholerae that was tested for the properties specific to V. cholerae O1. The designation O999 was used when no typing was utilized beyond species, e.g., the serotype of V. cholerae was not reported or investigated further. NA was provided when the prevalence was zero, and no serotype was applicable. When multiple serotypes were reported, but not tied to records, we specified that in the column, and when serotypes were provided and could be tied to a record, we noted that in the column as well

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
American Coot	*Fulica americana*	Rallidae	0	13	0%	United States	1990	None reported	NA	Cox (1992)
American Coot	*Fulica americana*	Rallidae	44	117	38%	United States	1989	None reported	O11, O14, O22, O23, O44, O106, O148, O176, O359, O999	Ogg et al. (1989)
American Coot	*Fulica americana*	Rallidae	1	2	50%	United States	1989	None reported	Non-O1	Siembieda et al. (2011)
American Flamingo	*Phoenicopterus ruber*	Phoenicopteridae	2	34	6%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
American Flamingo	*Phoenicopterus ruber*	Phoenicopteridae	3	9	33%	Mexico	1991	None reported	Non-O1	Aguirre et al. (1991)
American Oystercatcher	*Haematopus palliatus*	Haematopodidae	4	15	27%	Peru	2021	None reported	Non-O1	Huamanchumo (2021)
American Robin	*Turdus americana*	Turdidae	0	13	0%	United States	2007	Unknown	NA	Siembieda et al. (2011)
American White Pelican	*Pelecanus erythrorhynchos*	Pelecanidae	10	51	20%	United States	1989	None reported	O17, O19, O22, O999	Ogg et al. (1989)
American Widgeon	*Mareca americana*	Anatidae	0	41	0%	United States	1990	No	NA	Cox (1992)
Anas spp.	Unknown	Anatidae	14	30	47%	Egypt	2020	None reported	Non-O1	Ismail et al. (2021)
Aves spp.	Unknown	Unknown	3	23	13%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Aves spp.	Unknown	Unknown	54	343	16%	Japan	2000	None reported	Non-O1	Watanabe et al. (2002)

(continued)

Table 15.1 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Aves spp.	Unknown	Unknown	2	7	29%	Denmark	1977	None reported	Non-O1	Song et al. (1998)
Aves spp.	Unknown	Unknown	61	123	50%	China	1994	None reported	Non-O1	Song et al. (1998)
Aves spp.	Unknown	Unknown	7	8	88%	Australia	1989	None reported	Non-O1	Myatt and Davis (1989)
Black Skimmer	*Rynchops niger*	Laridae	0	1	0	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Black-and-white Magpie	*Pica hudsonia*	Corvidae	2	5	40%	Romania	2021	No	O999	Páll et al. (2021)
Black-bellied Whistling Duck	*Dendrocygna autumnalis*	Anatidae	3	110	3%	Mexico	1992	No	Non-O1	Aguirre et al. (1992)
Black-crowned Night Heron	*Nycticorax nycticorax*	Ardeidae	3	19	16%	United States	1989	None reported	O60, O999	Ogg et al. (1989)
Black-crowned Night Heron	*Nycticorax nycticorax*	Ardeidae	4	16	25%	United States	2007	None reported	Non-O1	Siembieda et al. (2011)
Black-crowned Night Heron	*Nycticorax nycticorax*	Ardeidae	7	8	88%	Israel	2018	None reported	O94	Laviad-Shitrit et al. (2018)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	0	5	0%	Israel	2018	None reported	NA	Laviad-Shitrit et al. (2018)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	7	142	5%	United Kingdom	1979	None reported	Multiple, not reported	Lee et al. (1982)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	4	55	7%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Black-necked Stilt	*Himantopus mexicanus*	Charadriidae	0	55	0%	China	2018	Yes	NA	Zheng et al. (2021)
Black-winged Stilt	*Himantopus himantopus*	Charadriidae	1	55	2%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Blue-winged Teal	*Anas discors*	Anatidae	1	80	1%	United States	1990	No	O999	Cox (1992)

Blue-winged Teal	*Anas discors*	Anatidae	12	39	31%	United States	1989	None reported	O19, O22, O23, O44, O106, O355, O360, O999	Ogg et al. (1989)
Brown Pelican	*Pelecanus occidentalis*	Pelecanidae	1	6	17%	United States	2007	None reported	Non-O1	Siembieda et al. (2011)
Bufflehead	*Bucephala albeola*	Anatidae	2	12	17%	United States	1990	No	O999	Cox (1992)
California Gull	*Larus californicus*	Laridae	1	93	1%	United States	1989	None reported	O22, O31, O340, O999	Ogg et al. (1989)
Canada Goose	*Branta canadensis*	Anatidae	2	4	50%	Canada	1985	Yes	Non-O1	Wobeser and Rainnie (1987)
Cattle Egret	*Bubulcus ibis*	Ardeidae	1	6	17%	United States	1989	None reported	O312, O359	Ogg et al. (1989)
Charadriiformes spp.	Unknown	Unknown	1	7	14%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Cinnamon Teal	*Spatula cyanoptera*	Anatidae	1	2	50%	United States	1989	None reported	O106, O999	Ogg et al. (1989)
Coal Tit	*Periparus ater*	Paridae	0	4	0%	Germany	1988	None reported	NA	Mehmke et al. (1992)
Mourning Dove and Band-tailed Pigeon	*Zenaida macroura* and *Patagioenas fasciata*	Columbidae	0	16	0%	United States	2007	None reported	NA	Siembieda et al. (2011)
Common Blackbird	*Turdus merula*	Turdidae	0	1	0%	Germany	1988	None reported	NA	Mehmke et al. (1992)
Common Chaffinch	*Fringilla coelebs*	Fringillidae	0	3	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Common Goldeneye	*Bucephala clangula*	Anatidae	0	1	0%	United States	1990	No	NA	Cox (1992)
Common Goldeneye	*Bucephala clangula*	Anatidae	1	1	100%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Common Greenshank	*Tringa nebularia*	Scolopacidae	0	2	0%	Romania	2021	No	NA	Páll et al. (2021)
Common Kingfisher	*Alcedo atthis*	Alcedinidae	0	1	0%	Romania	2021	No	NA	Páll et al. (2021)

(continued)

Table 15.1 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Common Moorhen	*Gallinula chloropus*	Rallidae	0	6	0%	United States	1990	No	NA	Cox (1992)
Common Murre	*Uria aalge*	Alcidae	3	31	10%	United States	2007	None reported	Non-O1	Siembieda et al. (2011)
Common Pochard	*Aythya ferina*	Anatidae	1	55	2%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Common Snipe	*Gallinago gallinago*	Scolopacidae	2	3	67%	Romania	2021	None reported	O999	Páll et al. (2021)
Common Tern	*Sterna hirundo*	Laridae	2	2	100%	Germany	2019	Yes	Non-O1	Strauch et al. (2020)
Domestic chicken	*Gallus gallus*	Phasianidae	24	250	10%	Bangladesh	2008	None reported	O999	Akond et al. (2008)
Domestic chicken	*Gallus gallus*	Phasianidae	4	22	18%	India	1973	None reported	O1 *El tor* Ogawa, Non-O1	Sanyal et al. (1974)
Domestic chicken	*Gallus gallus*	Phasianidae	2	7	29%	Unknown	1977	None reported	Non-O1	Sakazaki and Shimada (1977)
Domestic chicken	*Gallus gallus*	Phasianidae	27	60	45%	Egypt	2020	None reported	Non-O1	Ismail et al. (2021)
Domestic chicken	*Gallus gallus*	Phasianidae	134	212	63%	Ghana	1973	Yes	O1 *El tor* Ogawa	Salles et al. (1976)
Domestic chicken	*Gallus gallus*	Phasianidae	1	1	100%	India	1975	None reported	O999	Singh et al. (1975)
Domestic Duck	Unknown	Anatidae	3	17	18%	Denmark	1975	Yes	Non-O1	Bisgaard and Kristensen (1975)
Domestic Duck	Unknown	Anatidae	51	80	64%	Denmark	1978	None reported	O34, O60, O34, O54, O2, O57	Bisgaard et al. (1978)
Domestic Duck	*Anas platyrhynchos*	Anatidae	1	1	100%	Germany	2017	Yes	Non-O1	Hirsch et al. (2020)
Domestic Duck	*Anas platyrhynchos*	Anatidae	1	1	100%	Germany	2016	Yes	Non-O1	Hirsch et al. (2020)
Domestic Duck	*Anas platyrhynchos*	Anatidae	1	1	100%	Germany	2011	Yes	Non-O1	Hirsch et al. (2020)

Domestic Duck	*Anas platyrhynchos*	Anatidae	1	1	100%	Germany	1996	Yes	Non-O1	Hirsch et al. (2020)
Domestic Goose	*Anser anser*	Anatidae	1	2	50%	United States	1980	Yes	Non-O1	Schlater et al. (1981)
Domestic Turkey	*Meleagris gallopavo*	Meleagrididae	0	20	0%	Egypt	2020	None reported	NA	Ismail et al. (2021)
Domestic Turkey	*Meleagris gallopavo*	Meleagrididae	1	23	4%	Germany	2012	Yes	Non-O1	Metzner et al. (2004)
Double-crested Cormorant	*Phalacrocorax auritus*	Phalacrocoracidae	32	84	38%	United States	1989	None reported	O12, O22, O23, O106, O360, O999	Ogg et al. (1989)
Eared Grebe	*Podiceps nigricollis*	Podicipedidae	1	2	50%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Eastern Spot-billed Duck	*Anas zonorhyncha*	Anatidae	3	55	5%	China	2018	Unknown	Non-O1	Zheng et al. (2021)
Elegant Tern	*Thalasseus elegans*	Laridae	0	51	0%	Mexico	2012	None reported	NA	Contreras-Rodríguez et al. (2019)
Eurasian Blue Tit	*Cyanistes caeruleus*	Paridae	0	5	0%	Germany	1988	None reported	NA	Mehmke et al. (1992)
Eurasian Hobby	*Falco subbuteo*	Falconidae	2	2	100%	Romania	2021	No	O999	Páll et al. (2021)
Eurasian Nuthatch	*Sitta europaea*	Paridae	1	5	20%	Germany	1988	None reported	Non-O1	Mehmke et al. (1992)
Eurasian Sparrowhawk	*Accipiter nisus*	Accipitridae	1	2	50%	Romania	2021	No	O999	Páll et al. (2021)
Eurasian Tree Sparrow	*Passer montanus*	Passeridae	0	1	0%	Germany	1988	None reported	NA	Mehmke et al. (1992)
Eurasian Tree Sparrow	*Passer montanus*	Passeridae	2	2	100%	Romania	2021	No	O999	Páll et al. (2021)
Eurasian Whimbrel	*Numenius phaeopus*	Scolopacidae	0	9	0%	Peru	2021	None reported	NA	Huamanchumo (2021)
Herring Gull	*Larus argentatus*	Laridae	1	55	2%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Herring Gull	*Larus argentatus*	Laridae	5	88	6%	United Kingdom	1979	None reported	Multiple, not reported	Lee et al. (1982)

(continued)

Table 15.1 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Franklin's Gull	*Leucophaeus pipixcan*	Laridae	8	41	20%	United States	1989	None reported	O11, O22, O43, O999	Ogg et al. (1989)
Gadwall	*Mareca strepera*	Anatidae	10	200	5%	United States	1990	No	O999	Cox (1992)
Gadwall	*Mareca strepera*	Anatidae	2	3	67%	United States	1990	None reported	O22	Ogg et al. (1989)
Great Black-backed Gull and Herring Gull	*Larus marinus* and *Larus argentatus*	Laridae	23	45	56%	United States	1990	None reported	Non-O1	Buck (1990)
Great Blue Heron	*Ardea herodias*	Ardeidae	11	24	46%	United States	1989	None reported	O22, O1 *El tor* Ogawa	Ogg et al. (1989)
Great Cormorant	*Phalacrocorax carbo*	Phalacrocoracidae	1	55	2%	China	2017	Unknown	Non-O1	Zheng et al. (2021)
Great Cormorant	*Phalacrocorax carbo*	Phalacrocoracidae	9	11	82%	Israel	2017	None reported	Non-O1	Laviad-Shitrit et al. (2017)
Great Spotted Woodpecker	*Dendrocopos major*	Picidae	0	1	0%	Germany	1988	None reported	Non-O1	Mehmke et al. (1992)
Great Tit	*Parus major*	Paridae	4	12	33%	Germany	1988	None reported	Non-O1	Mehmke et al. (1992)
Greater Black-backed Gull	*Larus marinus*	Laridae	3	15	20%	United Kingdom	1979	None reported	Multiple, not reported	Lee et al. (1982)
Greater Scaup	*Aythya marila*	Anatidae	0	1	0%	United States	1990	None reported	NA	Cox (1992)
Greater Scaup	*Aythya marila*	Anatidae	2	3	67%	United States	2007	Unknown	NA	Siembieda et al. (2011)
Greater Yellowlegs	*Tringa melanoleuca*	Scolopacidae	6	6	100%	Venezuela	2006	None reported	O1 *El tor* Inaba	Rodríguez et al. (2010)
Green Heron	*Butorides virescens*	Ardeidae	2	8	25%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Green-winged Teal	*Anas carolinensis*	Anatidae	2	35	6%	United States	1989	None reported	O22, O106, O999	Ogg et al. (1989)
Green-winged Teal	*Anas carolinensis*	Anatidae	15	255	6%	United States	1990	No	O999	Siembieda et al. (2011)

Grey Gull	*Leucophaeus modestus*	Laridae	0	5	0%	Peru	2021	None reported	NA	Huamanchumo (2021)
Guanay Cormorant	*Leucocarbo bougainvilliorum*	Phalacrocoracidae	0	1	0%	Peru	2021	None reported	NA	Huamanchumo (2021)
Heermann's Gull	*Larus heermanni*	Laridae	0	44	0%	Mexico	2012	None reported	NA	Contreras-Rodríguez et al. (2019)
Heron spp.	Unknown	Ardeidae	1	6	17%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Hooded Merganser	*Lophodytes cucullatus*	Anatidae	0	3	0%	United States	1990	No	O999	Cox (1992)
House Crow	*Corvus splendens*	Corvidae	3	3	100%	India	1970	None reported	O17, O23, O308	Sack (1973)
Ibis spp.	Unknown	Threskiornithidae	0	3	0%	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Indian Spot-billed Duck	*Anas poecilorhyncha*	Anatidae	0	55	0%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Indian Spot-billed Duck	*Anas poecilorhyncha*	Anatidae	2	2	100%	China	1996	Yes	Multiple, not reported	Zhang et al. (1996)
Kelp Gull	*Larus dominicanus*	Laridae	5	11	45%	Brazil	2009	None reported	Non-O1	Cardoso et al. (2018)
Killdeer	*Charadrius vociferus*	Charadriidae	0	2	0%	Peru	2021	None reported	NA	Huamanchumo (2021)
Killdeer	*Charadrius vociferus*	Charadriidae	13	15	87%	United States	1989	None reported	O22, O106, O999	Ogg et al. (1989)
Large-billed Tern	*Phaetusa simplex*	Laridae	1	1	100%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Laughing Gull	*Leucophaeus atricilla*	Laridae	1	7	14%	Peru	2021	None reported	Non-O1	Huamanchumo (2021)
Least Sandpiper	*Calidris minutilla*	Scolopacidae	0	1	0%	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Lesser Scaup	*Aythya affinis*	Anatidae	0	8	0%	United States	1990	No	NA	Cox (1992)

(continued)

Table 15.1 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Little Egret	*Egretta garzetta*	Ardeidae	5	11	45%	Israel	2018	None reported	O13, O16, O36, O128, O171, O40, O6, O21, O123, O193, O36	Laviad-Shitrit et al. (2018)
Magnificent Frigatebird	*Fregata magnificens*	Fregatidae	0	1	0%	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Mallard	*Anas platyrhynchos*	Anatidae	0	32	0%	United States	1990	None reported	NA	Cox (1992)
Mallard	*Anas platyrhynchos*	Anatidae	27	306	9%	United States	1989	None reported	O22, O48, O999	Ogg et al. (1989)
Mallard	*Anas platyrhynchos*	Anatidae	2	12	17%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Mallard	*Anas platyrhynchos*	Anatidae	17	29	59%	Hungary	1979	None reported	Non-O1	Szeness et al. (1979)
Mallard	*Anas platyrhynchos*	Anatidae	2	2	100%	China	1996	None reported	Multiple, not reported	Zhang et al. (1996)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	1	35	3%	Brazil	2014	None reported	Non-O1	Cardoso et al. (2014)
Mottled Duck	*Anas fulvigula*	Anatidae	2	123	2%	United States	1990	None reported	O999	Cox (1992)
Mute Swan	*Cygnus olor*	Anatidae	2	2	100%	United Kingdom	1979	None reported	O2	Lee et al. (1982)
Neotropic Cormorant	*Phalacrocorax brasilianus*	Phalacrocoracidae	0	3	0%	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Northern Pintail	*Anas acuta*	Anatidae	0	53	0%	United States	1990	No	NA	Cox (1992)
Northern Pintail	*Anas acuta*	Anatidae	5	56	9%	United States	1989	None reported	O22, O360, O999	Ogg et al. (1989)
Northern Shoveler	*Spatula clypeata*	Anatidae	3	37	8%	United States	1990	No	O999	Cox (1992)

Parus spp.	Unknown	Paridae	4	22	18%	Germany	1988	None reported	Non-O1	Mehmke et al. (1992)
Passerine spp.	Unknown	Unknown	Not reported	Not reported	NA	Germany	1988	None reported	Non-O1	Mehmke et al. (1992)
Passerines	Unknown	Unknown	0	24	0%	United States	2007	Unknown	NA	Siembieda et al. (2011)
Peruvian Booby	*Sula variegata*	Sulidae	1	1	100%	Peru	2021	None reported	Non-O1	Huamanchumo (2021)
Peruvian Pelican	*Pelecanus thagus*	Pelecanidae	1	1	100%	Peru	2021	None reported	Non-O1	Huamanchumo (2021)
Red-footed Falcon	*Falco vespertinus*	Falconidae	2	2	100%	Romania	2021	None reported	Non-O1	Páll et al. (2021)
Redhead	*Aythya americana*	Anatidae	0	1	0%	United States	1990	None reported	O999	Cox (1992)
Redhead	*Aythya americana*	Anatidae	1	17	6%	United States	1989	None reported	O999	Ogg et al. (1989)
Rhinoceros auklet	*Cerorhinca monocerata*	Alcidae	1	1	100%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Ring-billed Gull	*Larus delawarensis*	Laridae	17	112	15%	United States	1989	None reported	O1 (not distinguished to Ogawa or Inaba), O16, O22, O102, O106, O999	Ogg et al. (1989)
Ring-necked Duck	*Aythya collaris*	Anatidae	4	37	11%	United States	1990	No	O999	Cox (1992)
Rook	*Corvus frugilegus*	Corvidae	1	28	4%	United Kingdom	1989	None reported	Multiple, not reported	Lee et al. (1982)
Ruddy Shelduck	*Tadorna ferruginea*	Anatidae	2	5	40%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Ruddy Shelduck	*Tadorna ferruginea*	Anatidae	25	55	45%	China	2018	Yes	Non-O1	Zheng et al. (2021)
Seabirds	Unknown	Unknown	1	192	0.5%	United States	2008	None reported	Non-O1	Bogomolni et al. (2008)
Seabirds	Unknown	Unknown	4	116	3%	Brazil	2010	None reported	Non-O1	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	Unknown	69	NA	Brazil	2010	None reported	O999	Roges et al. (2010)

(continued)

Table 15.1 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Semipalmated Plover	*Charadrius semipalmatus*	Scolopacidae	0	1	0%	Venezuela	2012	None reported	NA	Fernández-Delgado et al. (2016)
Semipalmated Sandpiper	*Charadrius pusilla*	Scolopacidae	1	2	50%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Snow Goose	*Chen caerulescens*	Anatidae	0	22	0%	United States	1990	No	NA	Cox (1992)
Snowy Egret	*Egretta thula*	Ardeidae	1	13	8%	United States	1989	None reported	O14, O340, O999	Ogg et al. (1989)
Song Thrush	*Turdus philomelos*	Turdidae	1	2	50%	Romania	2021	No	Non-O1	Páll et al. (2021)
Squacco Heron	*Ardeola ralloides*	Ardeidae	1	2	50%	Romania	2021	No	Non-O1	Páll et al. (2021)
Surf Scoter	*Melanitta perspicillata*	Anatidae	6	11	54%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Wading bird spp.	Unknown	Unknown	2	2	100%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Wattled Jacana	*Jacana jacana*	Jacanidae	2	6	33%	Venezuela	2012	None reported	Non-O1	Fernández-Delgado et al. (2016)
Western Grebe	*Aechmophorus occidentalis*	Podicipedidae	2	12	17%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Western Gull	*Larus occidentalis*	Laridae	1	7	14%	United States	2007	Unknown	Non-O1	Siembieda et al. (2011)
Western Jackdaw	*Coloeus monedula*	Corvidae	0	4	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Western Scrub-Jay	*Aphelocoma californica*	Corvidae	0	12	0%	United States	2007	Unknown	NA	Siembieda et al. (2011)
White Pekin Duck	*Anas platyrhynchos domesticus*	Anatidae	2	187	1%	United States	1993	Yes	O999	Watts et al. (1993)

White-faced Ibis	*Plegadis chihi*	Threskiornithidae	1	30	3%	United States	1989	None reported	O14	Ogg et al. (1989)
Wilson's Phalarope	*Phalaropus tricolor*	Scolopacidae	6	11	55%	United States	1989	None reported	O999	Ogg et al. (1989)
Wilson's Plover	*Charadrius wilsonia*	Charadriidae	16	16	100%	Venezuela	2006	None reported	Non-O1	Rodríguez et al. (2010)
Wood Duck	*Aix sponsa*	Anatidae	0	3	0%	United States	1990	None reported	NA	Cox (1992)
Wood Duck	*Aix sponsa*	Anatidae	0	55	0%	China	2018	Yes	NA	Zheng et al. (2021)
Yellow-legged Gull	*Larus michahellis*	Laridae	1	93	1%	France	2013	None reported	Non-O1	Aberkane et al. (2015)

Table 15.2 This table details the study records extracted from the 20 studies that investigated birds as hosts for *Vibrio parahaemolyticus*. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for *Vibrio parahaemolyticus*, the total number of birds examined for *V. parahaemolyticus*, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column. For serotypes or strains, we identified the strain when it was available. NA was provided when the prevalence was zero, and no strain was applicable

Avian Species	Scientific name	Family	Number positive	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
American Coot	*Fulica americana*	Rallidae	0	13	0%	United States	1990	None reported	Not specified	Cox (1992)
American Widgeon	*Mareca americana*	Anatidae	3	41	7%	United States	1990	None reported	Not specified	Cox (1992)
Anas spp.	Unknown	Anatidae	57	171	33%	Japan	2005	None reported	Not specified	Miyasaka et al. (2006)
Aves spp.	Unknown	Unknown	0	298	0%	China	2019	None reported	Not specified	Zheng et al. (2020)
Aves spp.	Unknown	Unknown	29	343	8%	Japan	2000	None reported	Not specified	Watanabe et al. (2002)
Aves spp.	Unknown	Unknown	1	8	13%	India	1986	None reported	Not specified	Karunasagar et al. (1986)
Aves spp.	Unknown	Unknown	4	8	50%	Australia	1989	None reported	Not specified	Myatt and Davis (1989)
Black-and-White Magpie	*Pica hudsonia*	Corvidae	0	5	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Black-crowned Crane	*Balearica pavonina*	Gruidae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Black-crowned Night Heron	*Nycticorax nycticorax*	Ardeidae	0	2	0%	Romania	1989	None reported	NA	Páll et al. (2021)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	68	125	54%	Japan	2005	None reported	NA	Miyasaka et al. (2006)
Black-tailed Godwit	*Limosa limosa*	Scolopacidae	1	2	50%	China	2005	None reported	Not specified	Wang et al. (2021)
Blue-winged Teal	*Anas discors*	Anatidae	0	80	0%	United States	1990	No	NA	Cox (1992)
Brown Pelican	*Pelecanus occidentalis*	Pelecanidae	20	42	48%	United States	1990	None reported	Not specified	Buck (1990)

Bufflehead	*Bucephala albeola*	Anatidae	1	12	8%	United States	1990	No	Not specified	Cox (1992)
Charadriiformes spp.	Unknown	Unknown	71	112	64%	China	2019	None reported	Not specified	Zheng et al. (2020)
Chinese Bamboo Partridge	*Bambusicola thoracicus*	Phasianidae	1	1	100%	Japan	1966	None reported	Biotype 2	Ose (1967)
Common Goldeneye	*Bucephala clangula*	Anatidae	0	1	0%	United States	1990	No	NA	Cox (1992)
Common Greenshank	*Tringa nebularia*	Scolopacidae	6	26	23%	China	2017	None reported	Not specified	Fu et al. (2019)
Common Greenshank	*Tringa nebularia*	Scolopacidae	2	5	40%	China	2015	None reported	Not specified	Wang et al. (2021)
Common Loon	*Gavia immer*	Gaviidae	1	434	0.2%	United States	1994	Yes	Not specified	Forrester et al. (1997)
Common Moorhen	*Gallinula chloropus*	Rallidae	0	6	0%	United States	1990	No	NA	Cox (1992)
Common Teal	*Anas crecca*	Anatidae	1	1	100%	Japan	2005	None reported	Not specified	Miyasaka et al. (2006)
Cormorant spp.	Unknown	Phalacrocoracidae	0	23	0%	China	2018	None reported	NA	Zheng et al. (2020)
Crested Fireback	*Lophura ignita*	Phasianidae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Crested Ibis	*Nipponia nippon*	Threskiornithidae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Demoiselle Crane	*Grus virgo*	Gruidae	0	125	0%	China	2019	None reported	NA	Zheng et al. (2020)
Elegant Tern	*Thalasseus elegans*	Laridae	1	51	2%	Mexico	2012	None reported	Not specified	Contreras-Rodríguez et al. (2019)
Eurasian Blackcap	*Sylvia atricapilla*	Sylviidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Eurasian Blue Tit	*Cyanistes caeruleus*	Paridae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Eurasian Curlew	*Numenius arquata*	Scolopacidae	1	2	50%	China	2015	None reported	NA	Wang et al. (2021)

(continued)

Table 15.2 (continued)

Avian Species	Scientific name	Family	Number positive	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Eurasian Sparrowhawk	*Accipiter nisus*	Falconidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Gadwall	*Mareca strepera*	Anatidae	16	200	8%	United States	1990	No	Not specified	Cox (1992)
Garden Warbler	*Sylvia borin*	Sylviidae	0	4	0%	Romania	2021	No	NA	Páll et al. (2021)
Great Argus	*Argusianus argus*	Phasianidae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Great Black-backed Gull and Herring Gull	*Larus marinus* and *Larus argentatus*	Laridae	23	45	56%	United States	1990	None reported	Not specified	Buck (1990)
Greater Scaup	*Aythya marila*	Anatidae	0	1	0%	United States	1990	None reported	NA	Cox (1992)
Green Pheasant	*Phasianus versicolor*	Phasianidae	1	1	100%	Japan	1965	No	Not specified	Ose (1967)
Green-winged Teal	*Anas carolinensis*	Anatidae	18	255	7%	United States	1990	No	Not specified	Siembieda et al. (2011)
Grey-hooded Parakeet	*Psilopsiagon aymara*	Psittacidae	0	1	0%	Germany	2020	Yes	NA	Reuschel et al. (2020)
Helmeted Guineafowl	*Numida meleagris*	Numididae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Heron spp.	Unknown	Ardeidae	26	89	29%	China	2018	None reported	Not specified	Zheng et al. (2020)
Herring Gull, Laughing Gull, Ring-billed Gull	*Larus argentatus*, *Leucophaeus atricilla*, *Larus delawarensis*	Laridae	29	42	69%	United States	1990	None reported	Not specified	Buck (1990)
Herring Gull and Ring-billed Gull	*Larus argentatus* and *Larus delawarensis*	Laridae	23	45	56%	United States	1990	None reported	Not specified	Buck (1990)
Herring Gull and Black-backed Gull	*Larus argentatus* and *Larus crassirostris*	Laridae	216	320	68%	Japan	2005	None reported	Not specified	Miyasaka et al. (2006)
Hooded Crow	*Corvus cornix*	Corvidae	0	7	0%	Romania	2021	None reported	NA	Páll et al. (2021)

Hooded Merganser	*Lophodytes cucullatus*	Anatidae	0	3	0%	United States	1990	None reported	NA	Cox (1992)
Icterine Warbler	*Hippolais icterina*	Acrocephalidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Japanese Quail	*Coturnix coturnix*	Phasianidae	Unknown	Unknown	Unknown	Korea	2011	None reported	ATCC 17802	Kassim et al. (2011)
Lady Amherst's Pheasant	*Chrysolophus amherstiae*	Phasianidae	1	1	100%	Japan	1965	None reported	Not specified	Ose (1967)
Lesser Scaup	*Aythya affinis*	Anatidae	0	8	0%	United States	1990	None reported	NA	Cox (1992)
Mallard	*Anas platyrhynchos*	Anatidae	2	32	6%	United States	1990	None reported	Not specified	Cox (1992)
Mallard	*Anas platyrhynchos*	Anatidae	72	267	27%	China	2018	None reported	Not specified	Zheng et al. (2020)
Mallard	*Anas platyrhynchos*	Anatidae	33	73	45%	Japan	2005	None reported	Not specified	Miyasaka et al. (2006)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	7	35	20%	Brazil	2014	None reported	Not specified	Cardoso et al. (2014)
Budgerigar	*Melopsittacus undulatus*	Psittaculidae	1	2	50%	Germany	2020	Yes	Not specified	Reuschel et al. (2020)
Mottled Duck	*Anas fulvigula*	Anatidae	5	123	4%	United States	1990	None reported	NA	Cox (1992)
Northern Pintail	*Anas acuta*	Anatidae	4	53	8%	United States	1990	None reported	Not specified	Cox (1992)
Northern Shoveler	*Spatula clypeata*	Anatidae	3	37	8%	United States	1990	None reported	Not specified	Cox (1992)
Red-backed Shrike	*Lanius collurio*	Laniidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Red-crowned Crane	*Grus japonensis*	Gruidae	0	26	0%	China	2018	None reported	NA	Zheng et al. (2020)
Redhead	*Aythya americana*	Anatidae	0	1	0%	United States	1990	None reported	NA	Cox (1992)
Reeve's Pheasant	*Syrmaticus reevesii*	Phasianidae	1	1	100%	Japan	1965	None reported	Not specified	Ose (1967)
Ring-necked Duck	*Aythya collaris*	Anatidae	0	37	0%	United States	1990	None reported	NA	Cox (1992)

(continued)

Table 15.2 (continued)

Avian Species	Scientific name	Family	Number positive	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Seabirds	Unknown	Unknown	0	192	0%	United States	2008	None reported	NA	Bogomolni et al. (2008)
Seabirds	Unknown	Unknown	4	116	3%	Brazil	2010	None reported	Not specified	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	Unknown	69	NA	Brazil	2010	None reported	Not specified	Roges et al. (2010)
Snow Goose	*Chen caerulescens*	Anatidae	0	22	0%	United States	1990	None reported	NA	Cox (1992)
Snowy Egret	*Egretta thula*	Ardeidae	1	2	50%	United States	1990	None reported	Not specified	Buck (1990)
Squacco Heron	*Ardeola ralloides*	Ardeidae	1	2	50%	Romania	2021	None reported	Not specified	Páll et al. (2021)
Swinhoe's Pheasant	*Lophura swinhoii*	Phasianidae	1	1	100%	Japan	1965	None reported	Biotype 1	Ose (1967)
Wood Duck	*Aix sponsa*	Anatidae	0	3	0%	United States	1990	None reported	Not specified	Cox (1992)

Table 15.3 This table details the records extracted from the eight studies that investigated birds as hosts for *Vibrio vulnificus*. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for *Vibrio vulnificus*, the total number of birds examined for the pathogen, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column. For serotypes or strains that were reported, we reported those as well, otherwise we designated the column as not specified

Avian Species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
American Crow	*Corvus brachyrhynchos*	Corvidae	Unknown	Unknown	Unknown	United States	2019	None reported	NA	Zhao et al. (2020)
Barred Warbler	*Curruca nisoria*	Sylviidae	0	3	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Black-crowned Night Heron	*Nycticorax nycticorax*	Ardeidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	1	125	1%	Japan	2005	None reported	Not specified	Miyasaka et al. (2006)
Black-tailed Godwit	*Limosa limosa*	Scolopacidae	1	2	50%	China	2015	None reported	Not specified	Wang et al. (2021)
Common Greenshank	*Tringa nebularia*	Scolopacidae	0	5	0%	China	2015	None reported	Not specified	Wang et al. (2021)
Common Teal	*Anas crecca*	Anatidae	0	1	0%	Japan	2005	None reported	NA	Miyasaka et al. (2006)
Domestic chicken	*Gallus gallus*	Phasianidae	4	565	0.7%	Nigeria	2017	None reported	Not specified	Adebowale and Adeyemo (2018)
Eurasian Blue Tit	*Cyanistes caeruleus*	Paridae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Common Teal	*Anas crecca*	Anatidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Garden Warbler	*Sylvia borin*	Sylviidae	0	4	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Herring Gull and Black-tailed Gull	*Larus argentatus* and *Larus crassirostris*	Laridae	86	320	27%	Japan	2005	None reported	NA	Miyasaka et al. (2006)
Hooded Crow	*Corvus cornix*	Corvidae	0	7	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Japanese Quail	*Coturnix coturnix*	Phasianidae	Unknown	Unknown	Unknown	Korea	2011	None reported	KCTC 2959	Kassim et al. (2011)
Laughing Gull	*Leucophaeus atricilla*	Laridae	Unknown	Unknown	Unknown	United States	2021	None reported	Not specified	Zhao et al. (2020)
Lesser Whitethroat	*Sylvia curruca*	Sylviidae	0	2	0%	Romania	2021	Not reported	NA	Páll et al. (2021)
Mallard	*Anas platyrhynchos*	Anatidae	0	73	0%	Japan	2005	None reported	NA	Miyasaka et al. (2006)
Muscovy Duck	*Cairina moschata*	Anatidae	Unknown	Unknown	Unknown	United States	2019	None reported	Not specified	Zhao et al. (2020)

(continued)

Table 15.3 (continued)

Avian Species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Seabirds	Unknown	Unknown	2	116	2%	Brazil	2010	None reported	Not specified	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	Unknown	69	NA	Brazil	2010	None reported	Not specified	Roges et al. (2010)
Wood Sandpiper	*Tringa glareola*	Scolopacidae	0	2	0%	Romania	2021	Not reported	NA	Páll et al. (2021)

Table 15.4 This table details the records extracted from the 15 studies that investigated birds as hosts for *Vibrio alginolyticus*. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for Vibrio cholerae, the total number of birds examined for *Vibrio alginolyticus*, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Kelp Gull	*Larus dominicanus*	Laridae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Not specified	de Moura et al. (2012)
Lesser Scaup	*Aythya affinis*	Anatidae	0	8	0%	United States	1990	None reported	NA	Cox (1992)
Magellanic Penguin	*Spheniscus magellanicus*	Spheniscidae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Not specified	de Moura et al. (2012)
Mallard	*Anas platyrhynchos*	Anatidae	0	32	0%	United States	1990	None reported	NA	Cox (1992)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	1	35	3%	Brazil	2014	None reported	Not specified	Cardoso et al. (2014)
Mauritius Kestrel	*Falco punctatus*	Falconidae	1	6	17%	Mauritania	1986	None reported	Not specified	Cooper et al. (1986)
Mottled Duck	*Anas fulvigula*	Anatidae	0	123	0%	United States	1990	None reported	NA	Cox (1992)
Mute Swan	*Cygnus olor*	Anatidae	2	3	67%	United States	1990	None reported	Not specified	Buck (1990)
Northern Pintail	*Anas acuta*	Anatidae	0	53	0%	United States	1990	None reported	NA	Cox (1992)
Northern Shoveler	*Spatula clypeata*	Anatidae	1	37	3%	United States	1990	None reported	Not specified	Cox (1992)
Red-backed Shrike	*Lanius collurio*	Laniidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Red-footed Falcon	*Falco vespertinus*	Falconidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Redhead	*Aythya americana*	Anatidae	0	1	0%	United States	1990	None reported	NA	Cox (1992)
Ring-necked Duck	*Aythya collaris*	Anatidae	1	37	3%	United States	1990	None reported	Not specified	Cox (1992)
Seabirds	Unknown	Unknown	8	192	4%	United States	2008	None reported	Not specified	Bogomolni et al. (2008)

(continued)

Table 15.4 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Seabirds	Unknown	Unknown	30	116	26%	Brazil	2010	None reported	Not specified	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	19	69	28%	Brazil	2010	None reported	Not specified	Roges et al. (2010)
Snow Goose	*Chen caerulescens*	Anatidae	0	22	0%	United States	1990	No	NA	Cox (1992)
Song Thrush	*Turdus philomelos*	Turdidae	0	2	0%	Romania	2021	No	NA	Páll et al. (2021)
Squacco Heron	*Ardeola ralloides*	Ardeidae	1	2	50%	Romania	2021	No	Not specified	Páll et al. (2021)
Wedge-tailed Shearwater	*Ardenna pacifica*	Procellariidae	24	246	10%	United States	1994	Yes	Not specified	Work and Rameyer (1999)
Wood Duck	*Aix sponsa*	Anatidae	0	3	0%	United States	1990	None reported	NA	Cox (1992)

Table 15.5 This table details the records extracted from the 15 studies that investigated birds as hosts for *Vibrio fluvialis*. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for *V. fluvialis*, the total number of birds examined for the pathogen, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column

Avian species	Scientific name	Family	Number positive	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
American Oystercatcher	*Haematopus palliatus*	Haematopodidae	2	15	13%	Peru	2021	None reported	Not specified	Huamanchumo (2021)
Aves spp.	Unknown	Unknown	4	8	50%	Australia	1989	None reported	Not specified	Myatt and Davis (1989)
Aves spp.	Unknown	Unknown	4	4	100%	Unknown	1983	None reported	Not specified	Shimada and Sakazaki (1983)
Brown Booby	*Sula leucogaster*	Sulidae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Not specified	de Moura et al. (2012)
Brown Pelican	*Pelecanus occidentalis*	Pelecanidae	20	42	48%	United States	1990	None reported	Not specified	Buck (1990)
Canada Goose	*Branta canadensis*	Anatidae	1	289	0.3%	Germany	2003	None reported	Not specified	Bönner et al. (2004)
Common Kingfisher	*Alcedo atthis*	Alcedinidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Domestic chicken	*Gallus gallus*	Phasianidae	10	10	100%	Iraq	2014	None reported	Not specified	Shnawa et al. (2014)
Domestic Duck	Unknown	Anatidae	5	Unknown	Unknown	Botswana	2010	Yes	Not specified	Moreki et al. (2011)
Eurasian Hobby	*Falco subbuteo*	Falconidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Eurasian Tree Sparrow	*Passer montanus*	Passeridae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Great Black-backed Gull and Herring Gull	*Larus marinus* and *Larus argentatus*	Laridae	23	45	56%	United States	1990	None reported	Not specified	Buck (1990)
Great Egret	*Ardea alba*	Ardeidae	3	11	27%	United States	2012	None reported	Not specified	Jubirt (2012)
Great Tit	*Parus major*	Paridae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Laughing Gull	*Leucophaeus atricilla*	Laridae	2	15	13%	Peru	2021	None reported	Not specified	Huamanchumo (2021)

(continued)

Table 15.5 (continued)

Avian species	Scientific name	Family	Number positive	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Serotypes or strains	Citation
Magellanic Penguin	*Spheniscus magellanicus*	Anatidae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Not specified	de Moura et al. (2012)
Mallard	*Anas platyrhynchos*	Anatidae	3	38	8%	Canada	1991	Yes	Not specified	Wobeser and Kost (1992)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	2	35	6%	Brazil	2014	None reported	Not specified	Cardoso et al. (2014)
Red-backed Shrike	*Lanius collurio*	Laniidae	0	1	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Red-footed Falcon	*Falco vespertinus*	Falconidae	0	2	0%	Romania	2021	None reported	NA	Páll et al. (2021)
Seabirds	Unknown	Unknown	0	192	0%	United States	2008	None reported	NA	Bogomolni et al. (2008)
Seabirds	Unknown	Unknown	9	116	3%	Brazil	2010	None reported	Not specified	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	Unknown	69	NA	Brazil	2010	None reported	Not specified	Roges et al. (2010)
Western Jackdaw	*Coleus monedula*	Corvidae	0	4	0%	Romania	2021	None reported	NA	Páll et al. (2021)

birds were tested for *Vibrio cholerae*, and 864 reported birds tested positive, for an overall meta-analysis prevalence of 16%. The prevalence of various studies ranged from 100% in case reports to zero, for example, this often represented rarely captured species that did not yield evidence of exposure to the pathogen. Mallards (*Anas platyrhynchos*) (*n* = 381) (Ogg et al. 1989; Cox 1992; Siembieda et al. 2011; Szeness et al. 1979; Zhang et al. 1996) appeared to be the most captured and examined wild species, while domestic chickens (*n* = 552), both backyard and experimentally inoculated, were the most commonly examined domestic species (Akond et al. 2008; Ismail et al. 2021; Salles et al. 1976; Sanyal et al. 1974; Singh et al. 1975; Sakazaki and Shimada 1977). Wilson's Plover (*Charadrius wilsonia*), a species of shorebird that was examined in Venezuela (*n* = 16/16), had the highest cross-sectional study prevalence for any wild bird captured, with a prevalence of 100% (Huamanchumo 2021). This was followed by Greater Yellowlegs (*Tringa melanoleuca*), also in Venezuela (*n* = 6/6), with a prevalence of 100% (Huamanchumo 2021), and Killdeer (*Charadrius vociferus*) in the western United States (*n* = 13/15), with a prevalence of 86.7% (Ogg et al. 1989).

Clinical signs were reported from 20 study records and were most often associated with *V. cholerae* non-O1/O139 (Aguirre et al. 1991; Bisgaard and Kristensen 1975; Hirsch et al. 2020; Metzner et al. 2004; Salles et al. 1976; Schlater et al. 1981; Strauch et al. 2020; Watts et al. 1993; Wobeser and Rainnie 1987; Zheng et al. 2020, 2021). One study reported clinical signs, primarily edema and cellulitis of the gastrointestinal tract, with an experimental inoculation of O1 Ogawa in domestic chickens (Salles et al. 1976). Clinical signs from the literature ranged from respiratory signs to lethargy and sepsis; most infections were associated with other pathogens. However, in a mortality study of American Flamingoes (*Phoenicopterus ruber*), *V. cholerae* infection was associated with lead toxicity (Aguirre et al. 1991). The largest cross-sectional study to examine wild birds who had exhibited clinical signs in the wild was performed in China, whereby Ruddy Shelducks (*Tadorna ferruginea*) (*n* = 25/55) tested positive for *V. cholerae* non-O1 (Zheng et al. 2021). This study also examined other taxa of birds, such as waterfowl, gulls, shorebirds, and Great Cormorants (*Phalacrocorax carbo*) for the presence of *Vibrio cholerae*, however, study-wide prevalences were generally low when associated with clinical signs (Table 15.1).

15.3.3 *Vibrio parahaemolyticus*

We identified 20 studies in the literature that examined the role of wild birds as hosts for *V. parahaemolyticus* (Ose 1967; Bogomolni et al. 2008; Buck 1990; Cardoso et al. 2014, 2018; Contreras-Rodríguez et al. 2019; Cox 1992; Myatt and Davis 1989; Páll et al. 2021; Roges et al. 2010; Watanabe et al. 2002; Zheng et al. 2020; Forrester et al. 1997; Fu et al. 2019; Karunasagar et al. 1986; Kassim et al. 2011; Miyasaka et al. 2006; Reuschel et al. 2020; Wang et al. 2021). We extracted seventy-three study records from these papers that examined the prevalence of the pathogen, however, in an additional two study records, we were unable to determine the number of birds infected and/or the number of birds tested (Roges et al. 2010; Kassim et al. 2011). One paper examined the immunogenicity of *V. parahaemolyticus* and *V. vulnificus* in Japanese Quail eggs (*Coturnix coturnix*) and found that birds elicited a high humoral response to the antigens, as measured by ELISA and Western Blots (Kassim et al. 2011). Most studies utilized culture to determine the presence of *V. parahaemolyticus*, or suckling mice coupled with culture, however, PCR and sequencing were more commonly utilized in more recent works. The Anatidae were represented by 21 study records, the Phasianidae (turkeys, chickens, and pheasants) represented nine study records, and the Laridae represented six study records. We were able to identify 60 species that had been examined for *V. parahaemolyticus*, representing 22 families. For eleven study records, we were unable to identify the species or family of the birds involved in the study (Bogomolni et al. 2008; Cardoso et al.

2018; Myatt and Davis 1989; Roges et al. 2010; Watanabe et al. 2002; Zheng et al. 2020; Karunasagar et al. 1986). Common Loons (*Gavia immer*) were the most common species tested for *V. parahaemolyticus*, after a multi-year mortality event in Florida (Forrester et al. 1997), however the prevalence was only 0.23% (1/434).

Similar to *V. cholerae*, prevalences for *V. parahaemolyticus* ranged from 100% in the cases of individual study records that were examined, or zero when relatively cryptic and/or scarce species were assessed. Out of the seventy-five study records that we extracted, only 44 reported study records contained birds that tested positive for the pathogen. The highest prevalence for wild birds captured in a cross-sectional study was 68%, involving three species of gulls: Herring Gulls (*Larus argentatus*), Laughing Gulls (*Leucophaeus atricilla*), and Ring-billed Gulls (*Larus delawarensis*) captured off the coast of Florida (Buck 1990). This was followed by Herring Gulls and Black-tailed Gulls (*Larus crassirostris*) captured off the coast of Japan, with a prevalence of 67% (Miyasaka et al. 2006). Across our study records, we found that 3996 birds had been tested for the presence of the pathogen or for antibodies against the pathogen. A total of 761 birds were positive for *V. parahaemolyticus*, for a meta-analysis prevalence of 19%. Clinical signs were only reported for two studies, in both, co-infection with other organisms was noted (Forrester et al. 1997; Reuschel et al. 2020). Four studies were associated with other *Vibrio* spp. that were not identified to species (Buck 1990; Cox 1992; Páll et al. 2021; Wang et al. 2021). Few studies overlapped between reporting both *V. cholerae* and *V. parahaemolyticus* in birds (Buck 1990; Cox 1992; Roges et al. 2010).

15.3.4 *Vibrio vulnificus*

Eight studies reported examining wild or domestic birds for the presence of *V. vulnificus* or *V. vulnificus* antibodies in the literature, from which we were able to extract 21 study records (Cardoso et al. 2018; Páll et al. 2021; Roges et al. 2010; Kassim et al. 2011; Miyasaka et al. 2006; Wang et al. 2021; Adebowale and Adeyemo 2018; Zhao et al. 2020). At least 17 species were represented in this dataset, categorized into 10 families. We were unable to determine within-study prevalences for five of those 21 study records, however, due to the pooling of samples (Roges et al. 2010; Kassim et al. 2011; Zhao et al. 2020). The most commonly utilized method of determining exposure to *V. vulnificus* in birds was the use of a biochemical panel coupled with culture (Páll et al. 2021; Adebowale and Adeyemo 2018); similar to *V. parahaemolyticus*, PCR and sequencing were more commonly used in later papers (Wang et al. 2021; Zhao et al. 2020). The prevalence of relevant studies ranged from zero for rarely captured and/or examined species to 50%, which was attributed to one of the two Black-tailed Godwits (*Limosa limosa*) captured in China that was positive by PCR and sequencing (Wang et al. 2021). This was followed by a prevalence of 26% for Herring Gulls and Black-tailed Gulls sampled off the coast of Japan (Miyasaka et al. 2006). The largest cross-sectional study was performed in Ogun State, Nigeria, from which multiple farms, representing 565 domestic chickens, were sampled for the presence of exposure to *V. vulnificus* (Adebowale and Adeyemo 2018). The study-wide prevalence was 0.7%.

No clinical signs or mortality events were reported from any study. In a cross-sectional sampling of urban birds in Houston, Texas, Zhao et al. (2020) reported that Muscovy Ducks (*Cairina moschata*) and Laughing Gulls excreted more *V. vulnificus* (*vvh*) than American Crows in the winter as compared to the summer. The greatest diversity of pathogenic *Vibrio* species was reported from a study of stranded seabirds ($n = 17/69$, *Vibrio* spp., prevalence of 25%) in Brazil, from which *V. vulnificus* was isolated along with *V. cholerae, V. parahaemolyticus, V. cincinnatiensis, V. fluvialis, V. harveyi*, and *V. mimicus* (Roges et al. 2010). The individual prevalence of *V. vulnificus*, or the avian species afflicted in this study was not reported, however a follow-up study reported a *V. vulnificus* prevalence of 1.7% in Brazilian seabirds (Cardoso et al. 2018). Overall, 1231 birds were examined for evidence of exposure to *V. vulnificus*, and 94 were positive, for a meta-analysis wide prevalence of 8%.

15.3.5 *Vibrio alginolyticus*

In the literature, we recovered 15 studies in which the role of domestic and wild birds as hosts for *V. alginolyticus* was examined, providing us with 49 study records (Bogomolni et al. 2008; Buck 1990; Cardoso et al. 2014, 2018; Contreras-Rodríguez et al. 2019; Cox 1992; Páll et al. 2021; Siembieda et al. 2011; Forrester et al. 1997; Kassim et al. 2011; Adebowale and Adeyemo 2018; Byrum and Slemons 1995; Cooper et al. 1986; de Moura et al. 2012; Work and Rameyer 1999). Two study records, involving seabirds off the coast of Brazil, did not identify the sampled birds to species (Cardoso et al. 2018; Roges et al. 2010). Forty-seven species were represented in this data subset, categorized into 18 families. Nineteen study records were attributed to the Anatidae, five study records to the Laridae, and three study records were represented by the Falconidae family, known for its small falcons and hawks. Culture, followed by biochemical panels, were the most commonly utilized methods to identify the pathogen. PCR was rarely utilized. The highest prevalence of *V. alginolyticus* recovered from a cross-sectional study of wild birds involved Herring Gulls, Laughing Gulls, and Ring-billed Gulls captured off the coast of Florida, with a prevalence of 68% (Buck 1990). The next highest prevalence of the pathogen was 55%, originating from Herring Gulls and Great Black-backed Gulls captured along coastal Connecticut (Buck 1990). Across the board, prevalences ranged from zero to 68%, no study record reached a prevalence of 100%. In a study performed in Ogun State, Nigeria, *V. alginolyticus* was isolated from 2% of domestic chickens (Adebowale and Adeyemo 2018).

Clinical signs and mortality were recorded by two studies, one involving a multi-year mortality event of Common Loons in Florida, and the second involved a mortality event off the coast of Oahu, Hawaii, of Wedge-tailed Shearwaters (*Ardenna pacifica*), which demonstrated a prevalence of 10% (Forrester et al. 1997; Work and Rameyer 1999). Clinical signs ranged from emaciation and lethargy to toxemia and sepsis; bacteremia in the case of the Wedge-tailed Shearwaters was strongly suspected (Forrester et al. 1997; Work and Rameyer 1999). In a diagnostic examination of critically endangered Mauritius Kestrels (*Falco punctatus*), a captive individual (1/6) was positive by culture for *V. alginolyticus,* yet no clinical signs were noted (Cooper et al. 1986). In general, waterfowl demonstrated the lowest prevalences for any group of birds, besides passerines, for the pathogen (Cox 1992; Páll et al. 2021). Throughout our dataset, 258 birds of 2967 sampled birds tested positive for *V. alginolyticus*, for a meta-analysis prevalence of 9%.

15.3.6 *Vibrio fluvialis*

From the literature, we found 15 studies that reported examining wild or domestic birds for the presence of *V. fluvialis* or *V. fluvialis* antibodies, from which we were able to extract 26 study records (Bogomolni et al. 2008; Buck 1990; Cardoso et al. 2014, 2018; Huamanchumo 2021; Myatt and Davis 1989; Páll et al. 2021; Roges et al. 2010; Kassim et al. 2011; de Moura et al. 2012; Bönner et al. 2004; Jubirt 2012; Moreki et al. 2011; Shimada and Sakazaki 1983; Shnawa et al. 2014; Wobeser and Kost 1992). At least 20 species were reported in this dataset, representing 15 families. Four records did not provide sufficient data from which to identify birds to species or family. Culture was the most commonly utilized method to identify *V. fluvialis*, followed by a biochemistry panel. The largest cross-sectional study examining the prevalence of *V. fluvialis* in wild birds was performed on Canada Geese in Germany, however, only one of 289 birds cultured positive for the pathogen (Bönner et al. 2004). *V. fluvialis* was associated with one mortality event—a die-off of overwintering Mallards in Canada which was attributed to a Vitamin A deficiency (Wobeser and Kost 1992). The reported prevalence of the pathogen for these birds was 8%. In a study of captive study of Great Egrets (*Ardea alba*) captured from the Mississippi Delta, control birds shed *V. fluvialis* for four of seven days in captivity (Jubirt 2012). The highest prevalence was associated with a study performed in Connecticut involving Herring Gulls and Great Black-backed Gulls, with 55% culturing positive for *V. fluvialis*. Studies with a prevalence of 100% involved two experiments, one involving of avian-sourced strains, and a mitogenicity study on domestic chickens (Shimada and Sakazaki 1983; Shnawa et al. 2014). Overall, the meta-analysis prevalence, including experimental infection studies (88/834) was 11% percent (85/834).

Other Pathogenic Vibrio spp.: *V. cincinnatiensis*, *V. hollisae*, e.g., *Grimontia hollisae*, *V. furnissii*, *V. mimicus*, *V. harveyi*, *V. scophthalmi*, *V. metschnikovii*, and *Photobacterium damselae.*

The abundance of studies that reported on other pathogenic *Vibrio* species that were isolated from wild or domestic birds varied (Table 15.6). *V. cincinnatiensis* was examined by five studies and provided five study records (Jäckel et al. 2020; Cardoso et al. 2014, 2018; Roges et al. 2010; de Moura et al. 2012). Unspecified seabirds were the taxa that were examined most frequently (Cardoso et al. 2018; Roges et al. 2010), however overall prevalences were low across all studies for a mean prevalence of 3%. The presence or absence of *Photobacterium damselae* was examined by three studies (Buck 1990; Forrester et al. 1997; Colvile et al. 2012), and yielded three study records from the United Kingdom and the United States. Two studies involved mortality events, one of Common Loons in Florida, and the second of British passerines (Forrester et al. 1997; Colvile et al. 2012). Across these cross-sectional studies, the overall meta-analysis prevalence was approximately 5%. Our literature search of *V. furnissii* yielded four study records from three cross-sectional studies (Cardoso et al. 2018; Huamanchumo 2021; de Moura et al. 2012), two of those study records did not identify the number of birds positive or the number of individuals examined. The Laridae were the most prevalent species identified in association with *V. furnissii*, specifically Kelp Gulls (*Larus dominicanus*), Laughing Gulls, and Brown Boobys (*Sula leucogaster*). The overall meta-analysis prevalence for this *Vibrio* pathogen was approximately 2%.

The search for studies involving *V. harveyi* and avian species yielded four cross-sectional studies and four study records (Cardoso et al. 2014, 2018; Roges et al. 2010; Wang et al. 2021), involving seabirds and Manx Shearwaters (*Puffinus puffinus*). A single study involving a coastal sandpiper, the Common Greenshank (*Tringa nebularia*), had a prevalence of 0% out of five birds that were tested by PCR (Wang et al. 2021). From the two studies that provided individual birds positive in contrast to individual birds examined, we were able to calculate a *V. harveyi* prevalence of approximately 13%. No study that tested for this pathogen reported clinical signs or a mortality event. *Grimontia hollisae* was rarely detected in birds, as we found only two studies, resulting in three study records, that searched for the pathogen in avian hosts (Fu et al. 2020; Albuixech-Martí et al. 2021). One study examined the shared microbiota between wild Hooded Cranes (*Grus monacha*) and domestic geese (*Anser anser*) using MiSeq—*Grimontia hollisae* was identified as a potential pathogen, but the total number of birds colonized was not reported (Fu et al. 2020). A longitudinal microbiome study involving shorebirds off the coast of Cork, Ireland discovered *Grimontia hollisae* in fecal samples, however, the number of samples positive/examined was not enumerated (Albuixech-Martí et al. 2021). Clinical signs or mortality were not reported from either study.

Vibrio metschnikovii was reported from three studies, resulting in 10 study records (Páll et al. 2021; Zheng et al. 2021; Lee et al. 1978). Approximately half the study records examined passerines of Romania as hosts (Páll et al. 2021), including members of the Laniidae, Sylviidae, and Paridae families, all of which were negative for the pathogen by biochemical panels. The highest prevalence was reported from sites in

Table 15.6 This table details the records extracted from the 18 studies that investigated birds as hosts for other pathogenic Vibrios, including *V. metschnikovii*, *V. mimicus*, *V. cincinnatiensis*, *V. scophtalmi*, *Grimontia hollisae*, formerly *V. hollisae*, *Photobacterium damselae*, formerly *V. damselae*, *V. furnissii*, and *V. harveyi*. In the table are provided the common name, the scientific name, the family, the number of birds that tested positive for the respective pathogen, the total number of birds examined, and the prevalence for that record. We also provide the country that the study was performed in, as well as the year the study was conducted or published. For studies that reported clinical signs or mortality, we placed a "Yes" in that column

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Pathogen	Citation
Barred Warbler	*Curruca nisoria*	Sylviidae	1	1	100%	Romania	2021	None reported	Vibrio metschnikovii	Páll et al. (2021)
Bearded Warbler	*Panurus biarmicus*	Paridae	0	3	0%	Romania	2021	None reported	Vibrio metschnikovii	Páll et al. (2021)
Black-and-White Magpie	*Pica hudsonia*	Corvidae	0	2	0%	Romania	2021	None reported	Vibrio metschnikovii	Páll et al. (2021)
Black-headed Gull	*Chroicocephalus ridibundus*	Laridae	13	34	38%	China	2018	Yes	Vibrio metschnikovii	Zheng et al. (2020)
Black-necked Stilt	*Himantopus mexicanus*	Charadriidae	1	34	3%	China	2018	Yes	Vibrio metschnikovii	Zheng et al. (2020)
Black-winged Stilt	*Himantopus himantopus*	Charadriidae	0	34	0%	China	2018	Yes	Vibrio metschnikovii	Zheng et al. (2020)
Common Kingfisher	*Alcedo atthis*	Alcedinidae	0	1	0%	Romania	2021	None reported	Vibrio metschnikovii	Páll et al. (2021)
Common Pochard	*Aythya ferina*	Anatidae	1	34	3%	China	2018	Yes	Vibrio metschnikovii	Zheng et al. (2020)
Common Whitethroat	*Curruca communis*	Sylviidae	0	5	0%	Romania	2021	None reported	Vibrio metschnikovii	Páll et al. (2021)
Domestic Chicken	*Gallus gallus*	Phasianidae	1	1	100%	Unknown	1978	None reported	Vibrio metschnikovii	Lee et al. (1978)
Domestic Goose	*Anser anser*	Anatidae	1	1	100%	Germany	2001	None reported	Vibrio cincinnatiensis	Jäckel et al. (2020)
Kelp Gull	*Larus dominicanus*	Laridae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Vibrio cincinnatiensis	de Moura et al. (2012)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	2	35	6%	Brazil	2014	None reported	Vibrio cincinnatiensis	Cardoso et al. (2014)
Seabirds	Unknown	Unknown	Unknown	69	Unknown	Brazil	2010	None reported	Vibrio cincinnatiensis	Roges et al. (2010)
Seabirds	Unknown	Unknown	2	116	2%	Brazil	2010	None reported	Vibrio cincinnatiensis	Cardoso et al. (2018)

(continued)

Table 15.6 (continued)

Avian species	Scientific name	Family	Number tested	Total examined	Prevalence	Country	Year	Clinical signs or mortality	Pathogen	Citation
Brown Pelican	*Pelecanus occidentalis*	Pelecanidae	20	42	48%	United States	1990	None reported	Photobacterium damselae	Buck (1990)
Common Loon	*Gavia immer*	Gaviidae	1	434	0.2%	United States	1994	Yes	Photobacterium damselae	Forrester et al. (1997)
Great Tit	*Parus major*	Paridae	1	5	20%	United Kingdom	2011	Yes	Photobacterium damselae	Colvile et al. (2012)
Kelp Gull	*Larus dominicanus*	Laridae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Vibrio furnissii	de Moura et al. (2012)
Brown Booby	*Sula leucogaster*	Sulidae	Unknown	Unknown	Unknown	Brazil	2011	None reported	Vibrio furnissii	de Moura et al. (2012)
Laughing Gull	*Leucophaeus atricilla*	Laridae	1	7	14%	Peru	2021	None reported	Vibrio furnissii	Huamanchumo (2021)
Seabirds	Unknown	Unknown	1	116	1%	Brazil	2010	None reported	Vibrio furnissii	Cardoso et al. (2018)
Seabirds	Unknown	Unknown	Unavailable	69	Unknown	Brazil	2010	None reported	Vibrio harveyi	Roges et al. (2010)
Common Greenshank	*Tringa nebularia*	Scolopacidae	0	5	0%	China	2015	None reported	Vibrio harveyi	Wang et al. (2021)
Manx Shearwater	*Puffinus puffinus*	Procellariidae	7	35	20%	Brazil	2014	None reported	Vibrio harveyi	Cardoso et al. (2014)
Seabirds	Unknown	Unknown	14	116	13%	Brazil	2010	None reported	Vibrio harveyi	Cardoso et al. (2018)
Aves	Unknown	Unknown	Unknown	204	Unknown	Ireland	2019	None reported	Grimontia hollisae	Albuixech-Martí et al. (2021)
Domestic Goose	*Anser anser*	Anatidae	Unknown	20	Unknown	China	2017	None reported	Grimontia hollisae	Fu et al. (2020)
Hooded Crane	*Grus monarcha*	Gruidae	Unknown	20	Unknown	China	2017	None reported	Grimontia hollisae	Fu et al. (2020)
Seabirds	Unknown	Unknown	Unknown	69	Unknown	Brazil	2010	None reported	Vibrio mimicus	Roges et al. (2010)
Bearded Reedling	*Panurus biarmicus*	Paridae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Black-tailed Godwit	*Limosa limosa*	Scolopacidae	3	26	12%	China	2018	None reported	Vibrio mimicus	Fu et al. (2019)
Common Chaffinch	*Fringilla coelebs*	Fringillidae	0	5	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)

Common Kingfisher	*Alcedo atthis*	Alcedinidae	0	1	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Common Snipe	*Gallinago gallinago*	Scolopacidae	0	3	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Domestic Chicken	*Gallus gallus*	Phasianidae	8	565	1%	Nigeria	2017	None reported	Vibrio mimicus	Adebowale and Adeyemo (2018)
Eurasian Blue Tit	*Cyanistes caeruleus*	Paridae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Eurasian Hobby	*Falco subbuteo*	Falconidae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Eurasian Stone Curlew	*Burhinus oedicnemus*	Burhinidae	1	61	2%	Italy	2018	None reported	Vibrio mimicus	Foti et al. (2020)
Great Tit	*Parus major*	Paridae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Hawfinch	*Coccothraustes coccothraustes*	Fringillidae	0	8	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Hooded Crow	*Corvus cornix*	Corvidae	0	7	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Lesser Whitethroat	*Sylvia curruca*	Sylviidae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Seabirds	Unknown	Unknown	8	116	7%	Brazil	2010	None reported	Vibrio mimicus	Cardoso et al. (2018)
Song Thrush	*Turdus philomelos*	Turdidae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Wood Sandpiper	*Tringa glareola*	Scolopacidae	0	2	0%	Romania	2021	None reported	Vibrio mimicus	Páll et al. (2021)
Common Greenshank	*Tringa nebularia*	Scolopacidae	1	26	4%	Romania	2021	None reported	Vibrio scophtalmi	Páll et al. (2021)

Inner Mongolia, China, by Black-headed Gulls (*Chroicocephalus ridibundus*), from which an overall study prevalence of 38% was reported (Zheng et al. 2021). Clinical signs and a mortality event that spanned multiple waterfowl and waterbird species were documented in the study by Zheng et al. (2021). The number of total tested birds was not available for analysis in the latter study; thus, we could not report a meta-analysis prevalence of *V. metschnikovii* with confidence. *Vibrio mimicus* was examined by six studies, yielding 18 study records (Cardoso et al. 2018; Páll et al. 2021; Roges et al. 2010; Fu et al. 2019; Adebowale and Adeyemo 2018; Foti et al. 2020). Biochemical panels were the most common diagnostic tool used to identify the pathogen, however, overall prevalences were very low across studies. In a study of wading birds and songbirds performed along the Danube Delta of Romania, all sampled birds ($n = 38$) were negative for *V. mimicus* (Páll et al. 2021). On the other hand, wading birds and seabirds sampled in China, Brazil, and Italy demonstrated evidence of shedding the pathogen (Cardoso et al. 2018; Fu et al. 2019; Foti et al. 2020). The only study to examine the role of domestic birds as hosts was performed in Ogun State, Nigeria—this study yielded a prevalence of approximately 1% (Adebowale and Adeyemo 2018). Across studies, 806 birds were examined for the presence of the pathogen, with 21 testing positive, resulting in a meta-analysis prevalence of 2%. No clinical signs or mortality events were reported from any study that examined the role of birds as hosts for *V. mimicus*.

Vibrio scophthalmi was only reported from one study, resulting in a single study record (Fu et al. 2019). A Common Greenshank (1/26) that was sampled using whole genome sequencing was positive for the pathogen (Fu et al. 2019). This study was not associated with clinical signs or a mortality event. Uncategorized *Vibrio* spp. were reported from 14 studies (Bogomolni et al. 2008; Buck 1990; Cardoso et al. 2018; Cox 1992; Fernández-Delgado et al. 2016; Huamanchumo 2021; Páll et al. 2021; Watanabe et al. 2002; Zheng et al. 2020; Wang et al. 2021; Albuixech-Martí et al. 2021; White et al. 1973; Negruțiu et al. 2017; Saiful Islam et al. 2021). Two studies were associated with clinical signs and/or mortality events, however, these outbreaks were attributed to other causal pathogens (Zheng et al. 2020; White et al. 1973). Culture followed by biochemical panels were the most commonly utilized methods of identifying *Vibrio* spp. Given that many studies did not identify these *Vibrio* spp. to species or identify the number of birds excreting them, we were unable to calculate a meta-analysis wide prevalence.

15.4 Discussion

The question of pathogenic *Vibrio* spp. as the etiological agents of disease in birds remains only partially answered. Of the 76 studies that surveyed birds for pathogenic *Vibrio* species, 19 reported disease or death from individuals, scaling up to community-level events (Aguirre et al. 1991; Bisgaard and Kristensen 1975; Hirsch et al. 2020; Metzner et al. 2004; Salles et al. 1976; Schlater et al. 1981; Strauch et al. 2020; Watts et al. 1993; Wobeser and Rainnie 1987; Zheng et al. 2020, 2021; Forrester et al. 1997; Reuschel et al. 2020; Work and Rameyer 1999; Moreki et al. 2011; Wobeser and Kost 1992; Colvile et al. 2012; Lee et al. 1978; White et al. 1973). Yet, it remains uncertain whether these pathogenic *Vibrio* species are opportunistic pathogens that contribute to morbidity and/or mortality in already stressed individuals, or whether they can be the primary arbiters of disease (Zhao et al. 2020). Experimental inoculation studies reported contrasting results, if they reported clinical signs at all (Laviad-Shitrit et al. 2017; Salles et al. 1976; Zhang et al. 1996; Shnawa et al. 2014). In addition, avian susceptibility to pathogenic *Vibrio* species may also be conflated by host species, natural history, and prior exposure, resulting in an as yet-understood degree of immunity (Roche et al. 2009; Gamble et al. 2019). In our meta-analysis, disease was most commonly associated with *V. cholerae*, followed by *V. metschnikovii* and *V. parahaemolyticus*—notably, 11 of 39 study records were associated with domestic ducks (*Anas platyrhynchos* or *Anser anser*) or domestic chickens (Bisgaard and Kristensen

1975; Bisgaard et al. 1978; Hirsch et al. 2020; Metzner et al. 2004; Salles et al. 1976; Watts et al. 1993). This may have implications for agriculturally associated species in areas of the world where backyard birds are the primary protein source for pastoral families (Conan et al. 2012; Hamilton-West et al. 2012; Kariithi et al. 2021).

Of the 425 study records we extracted from the literature, interestingly, the Anatidae represented 105 of them, including wild and domesticated Mallards, which represented 16 study records. The Laridae represented 39 study records, prominently represented by Laughing Gulls, Herring Gulls, and Ring-billed Gulls. Shorebirds and waders, categorized into the Ardeidae family, represented 16 study records, primarily of egrets and herons. These bird species are often highly associated with coastal estuarine and marine environments (Barnes and Thomas 1987; Waldenström et al. 2002; Chatterjee et al. 2020), which are also inhabited by autochthonous and halophilic *Vibrio* species. These results are congruent with what is known of avian foraging ecology and *Vibrio* habitat specificity (Pruzzo et al. 2005; Almagro-Moreno and Taylor 2014; Vezzulli et al. 2010; Grimes et al. 2009; Johnson et al. 2012; Grimes 2020). What was unexpected were the number of ground-foraging birds that tested positive for pathogenic *Vibrio* species that are often not strictly associated with aquatic environments, such as Great Tits (*Parus major*), Garden Warblers (*Sylvia borin*), and Hooded Crows (*Corvus cornix*) (Mehmke et al. 1992; Páll et al. 2021).

For example, in a study of Egyptian backyard poultry (chickens, turkeys, and waterfowl), 36% of examined birds were positive for *V. cholerae,* including chickens and turkeys (Ismail et al. 2021). Domestic chickens accounted for 13 total study records, across geographical areas as varied as the United States, Bangladesh, Egypt, Ghana, Nigeria, Iraq, and India, and reported as early as 1972 (Akond et al. 2008; Ismail et al. 2021; Salles et al. 1976; Sanyal et al. 1974; Singh et al. 1975; Sakazaki and Shimada 1977; Adebowale and Adeyemo 2018; Byrum and Slemons 1995; Shnawa et al. 2014; Lee et al. 1978). On the other hand, another surprising result was the low prevalence of pathogenic *Vibrio* species cultured from seabirds that were sampled from the New England region of the United States, with only one of 192 birds testing positive for *Vibrio cholerae*, non-O1 (Bogomolni et al. 2008). This result may be due to several reasons, many of which are not mutually exclusive (Chatterjee et al. 2020). For one, as seabirds tend to spend more time in marine versus coastal habitats, they may be less susceptible to exposure from pathogenic *Vibrio* species that tend to congregate in lower salinity, brackish habitats (Hsieh et al. 2008). In addition, the northern Atlantic may harbor a lower abundance of pathogenic *Vibrios* during the cooler months as a result of low sea surface temperatures (Baker-Austin et al. 2010, 2012). Lastly, it may be possible that although pathogenic *Vibrio* spp. may cause disease in seabirds, that the recovery of carcasses or diseased individuals may be reduced due to minimal mortality, low carcass persistence, and increased distances from urbanized centers (Piatt and Ford 1996; Ford 2006; Ward et al. 2006).

Meta-analysis prevalence varied across pathogenic *Vibrio* species, but all were below 20% (e.g., 19% for *V. parahaemolyticus,* 16% for *V. cholerae*, 13% for *V. harveyi*, 11% for *V. fluvialis*, 9% for *V. alginolyticus*, 8% for *V. vulnificus*, 5% for *P. damselae*, 2% for *V. furnissii*, and 1% for *V. mimicus*). Given that we utilized experimental inoculation studies coupled with cross-sectional studies, there is likely a degree of reporting bias in our meta-analysis prevalences (Lachish and Murray 2018), however, we speculate that this reporting bias is likely offset by the reportedly few studies that have targeted these pathogens for investigation in wild and domestic birds. To determine true "prevalence," and avian susceptibility under ecological conditions, longitudinal studies that sought to recover these pathogens from a community of birds would be more informative (Wobeser 2007; Brown et al. 2013). In addition, these studies would need to utilize large sample sizes, as well as represent various ecological foraging guilds, in geographic locations with both low and high recovery rates of these pathogens from their aquatic, environmental reservoir

(Stallknecht 2007; Cardoso et al. 2021; Watsa and Wildlife Disease Surveillance Focus Group 2020; Sleeman et al. 2012).

With a meta-analysis *Vibrio* prevalence of 16% coupled with the reports of clinical signs, there is a possibility that pathogenic *Vibrio* species—specifically *V. parahaemolyticus, V. cholerae,* and *V. metschnikovii*—may be emerging pathogens of wild and domestic aquatic or wetland birds (Daszak et al. 2000; Robinson et al. 2010). Gire et al. (2012) defined emerging pathogens as falling into two categories: introduced microbes and existing microbes that rapidly increase in prevalence and/or incidence in a population. Given that so little is known of non-cholera *Vibrio* species in human hosts, however, it is difficult to distinguish between the two categories in our avian hosts given the currently available data. Speculation suggests that these *Vibrio* pathogens may have a long-standing relationship with aquatic birds. However, as climate change alters and influences the abundance and distribution of pathogenic *Vibrio* species in marine and estuarine environments, so too may the incidence of these pathogens in wild and domestic birds (Fuller et al. 2012).

In summary, we have offered a rigorous meta-analysis that examines the prevalence of *Vibrio* spp. across bird species. In doing so, we also reveal a plethora of data that fortifies the notion that birds are both an underappreciated object of study and potential reservoirs for pathogenic bacterial species. In the context of a dynamic ecology defined by climate change and human-associated activities, we suggest that avian reservoirs should be the focus of more rigorous study, as they may be an actor in *Vibrio* emergence events. Transcending the case of birds, our study proposes that more attention should be paid to animal species that may harbor pathogens of interest to human health.

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