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Avian haemosporidian parasites: An updated review

*Wafaa A. Abd El-Ghany[1]

[1]Poultry Diseases Department, Faculty of Veterinary Medicine, Cairo University, Giza, 12211, Egypt http://orcid.org/0000-0003-1686-3831

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* *Corresponding author: Wafaa A. Abd El-Ghany, wafaa.soliman@cu.edu.eg*

Abstract: Avian hosts are vulnerable to many infectious agents including parasitic diseases. Haemosporidians (Sporozoa: Haemosporida) is a group of internal parasites of blood that infect domestic and wild birds causing loss of productivity and sometimes death. More than 200 species of haemosporidian parasites were identified in the blood and tissues of avian hosts. However, *Leucocytozoon*, *Plasmodium*, and *Haemoproteus* spp. are the most common and widely distributed haemosporidian parasites. Insect vectors including Culex mosquitoes, *Simulium* spp., midges or hippoboscid flies, and *Argas persicus* are the main route of infection and transmission of haemosporidian parasites. Climatic conditions such as temperature, humidity, and vector activities can also play an important role in the distribution of infections. Affected birds may show no clinical signs during mild infection, however, signs of loss of weight, drop in egg production, anemia, anorexia, pale comb, green droppings, dyspnea, and variable mortalities may be observed especially in heavy infection. Different lesions in the internal organs such as the liver, spleen, and kidneys can be detected. Diagnosis of haemosporidian parasites is mainly based on microscopic examination of stained blood smears and/or molecular identification of the different stages of the parasite in the blood or tissues. Control of infection depends on the eradication of insects and the treatment of the affected birds using specific drugs. This review article was designed to take a look at avian haemosporidian parasites regarding types, distribution, diagnosis, and control.

Keywords: birds; blood parasites; diagnosis; distribution; treatment.

1. Introduction

Avian species are susceptible to numerous types of bacterial, viral, fungal, and parasitic infections. Among the various parasitic diseases of poultry, haemoparasitic infections are considered very significant (Dunn and Outlaw, 2019). Haemosporidians (Sporozoa: Haemosporida) are a group of endoparasites of blood that inhabit a broad range of avian species (Sehgal, 2015). The significant economic importance of blood parasites include increasing mortalities (Valkiūnas, 2005), retardation of growth, and reproductive failure (Marzal et al., 2005). A reduced immune response is a sequence of events due to the destruction of immunological cells such as white blood cells (La Puente et al., 2010).

There are more than 200 species of identified avian blood protozoon parasites (Atkinson et al., 2009). The common avian haemoprotozoans are *Leucocytozoon*, *Plasmodium*, *Haemoproteus*, *Aegyptinella*, Eperythrozoon, *Fallisia*, *Haemobartonella*, and *Trypanosomes* spp. (Mohammed et al., 2019). Nematode *Microfilariae* are also common in the blood of birds (Silveira et al., 2010). Besides, sporozoan *Hepatozoon*, *Babesia*, and *Atoxoplasma* genera are other vector-borne avian blood parasites. Blood parasites show some stages of development in both tissues and circulating red blood cells (RBCs) of the infected hosts. Wild and domestic birds are vulnerable to that intracellular haemosporidian (Buranapim et al., 2019; Lawal et al., 2021; Sadaf et al., 2021; Aiyedun et al., 2022). However, *Haemoproteus* and *Leucocytozoon* spp. are somewhat host-specific and restricted to species of birds in the same family. *Plasmodium* spp. show a much broader host specific and may infest several families of birds by changing their morphology and genetic characters (Atkinson, 1986). Free-ranging birds act as a link between commercial poultry and wild bird populations. Accordingly, the free-range breeding systems show high incidences and susceptibility to this type of parasitic *infestation* (Opara et al., 2014).

The life cycles of haemoparasites are closely related to their arthropod vectors and vector-parasite compatibility. Moreover, vectors of these haemoparasites are mainly blood-sucking dipteran insects which belong to 17 genera (Ziegyte and Valkiūnas, 2014). For instance, avian *Plasmodium*, *Leucocytozoon*, *Haemoproteus*, Aegyptianella, and *Trypanosomes* spp. are transmitted via mosquitoes, *Simulium* spp., midges or hippoboscid flies, *Argas persicus*, and Culex spp., respectively (Svobodova et al., 2015; Ogbaje et al., 2019).

The interaction between the blood parasites and the avian host is complex (Martinez and Merino, 2011). Factors that influence the prevalence's variations of haemosporidian in avian communities may include environmental conditions, species, age, sex, and the reproductive and behavioral status of the host, as well as the presence of vectors (Laurance et al., 2013; Rodrigues et al., 2021). Climatic changes such as warm and dry climates reduce the prevalence of blood parasites (Mirzaei et al., 2020; Castaño Vázquez and Merino, 2022). When the vector populations are low, infected birds may show no clinical manifestations but parasites can survive during dry seasons. Haemoparasites might induce depression, anorexia, reduced productivity, growth retardation, green feces, dyspnea, and mortality, and having a negative influence on the birds' behavior (Sørci and Møller, 1997; Dunn et al., 2011).

The diagnosis of blood parasites has relied on the conventional microscopic examination of stained blood smears and/or the molecular techniques using polymerase chain reaction (PCR) assays (Tostes et al., 2015; Bernotienė et al., 2016; Chawengkirttikul et al., 2021). Insufficient preventive or treatment measures could increase infection rates and birds mortality (Pérez-Tris and Bensch, 2005). Therefore, the main objective of the present review article was to describe the avian haemosporidian parasites regarding their genus/species, world distribution, ways of diagnosis, and methods of contro*L*.

2. Different avian haemosporidian parasites

2.1. *Leucocytozoon* spp.

*Leucocytozoon*osis is a protozoan disease that affects the blood and the internal organs of different avian species (Forrester and Greiner, 2008). Chickens, turkeys, pigeons, raptors, waterfowl, ostriches, and wild birds are susceptible to such infection (Bennett et al., 1993). *Leucocytozoon* (*L.*) spp. are named according to the species of birds in which they were detected. For instance, *L.* smithi in turkeys, *L. sabrazesi* in fowl, *L. simondi* and *L. caulleryi* in anseriformes, *L. marchouxi* in columbiformes, *L. toddi* in falconiformes, and *L. ziemanni* in owls (Soulsby, 1982). *Leucocytozoon* spp. are generally transmitted by insect vectors such as *Culicoides* midges and *Simuliidae* (black fly) spp. (Desser and Bennett, 1993). *Leucocytozoon* spp. have a complex life cycle; a schizogony (merogony) stage in tissues, a sexual (gametogony) stage in RBCs or leukocytes of vertebrates, and a sporogony stage in simuliid fly or culicids midges (Valkiūnas 2005). Biting of the host with the mosquito vectors results in the inoculation of sporozoites in the blood and then attacks the endothelial cells of the lung, liver, and spleen (Zhao et al., 2015). In the liver cells and vascular endothelium of other tissues, the sporozoites of *Leucocytozoon* spp. transform to small schizonts and megaloschizonts, and then form gametocytes in the erythroblasts and mononuclear leucocytes (Zhao et al., 2015). Yin et al. (2002) found that intravenous inoculation of *L. caulleryi* sporozoites in 26-day-old chickens induced early production of schizonts in the lung, spleen, and thymus at the 6th-day post-inoculation. Moreover, *L. simondi* was detected as a comma shape parasite in the hepatocytes, alveolar epithelial cells of lungs, and renal tubules of ducks' tissues (Shutler et al., 1999; Dey et al., 2008).

Heavy infections with *Leucocytozoon* could lead to a high mortality rate (Hunter et al., 1997). Naturally infected chickens with *L. sabrazesi* may show acute mortality of more than 50%, or chronic drop in egg production, depression, anorexia, anemia, pale comb, and green droppings (Zhao et al., 2015). In South Korea, an outbreak of *L. caulleryi* infection has been histopathologically and molecularly detected in a broiler breeder chicken flock with a history of depression, sudden death, and subcutaneous hemorrhages in the wings and legs, muscles, thymus, epicardium, pancreas, and kidneys (Lee et al., 2014). A further study by Lee et al. (2016) showed mortality and decreased egg production in 59 and 82-week-old layer chickens due to *L. caulleryi* infection. Dead birds displayed enlarged, fragile, yellowish, and hemorrhagic livers, and the protozoon megaloschizonts were microscopically and molecularly detected in the liver and ovaries tissues (Lee et al., 2016). Moreover, naturally infected Pekin ducklings with *L. simondi* showed anemia, gametocytaemia, and osmotic fragility of erythrocytes (Maley and Desser, 1977).

2.2. *Plasmodium* spp.

Avian malaria is a parasitic disease caused by protozoan parasites of the *Plasmodium* genus (Jennings et al., 2006). This genus has a close linkage to *Haemoproteus* and *Leucocytozoon* genera. Over 65 *Plasmodium* spp. have been detected in more than 1.000 different avian hosts. However, *P. gallinaceum*, *P. juxtanucleare*, and *P. durae* are the most pathogenic to avian species and cause a 90% mortality rate (Springer, 1991). Additionally, *P. gallinaceum*, in particular, is known to cause severe illness and mortality rates up to 30% to 80% (Soulsby, 1982). The transmission of *Plasmodium* spp. to birds via mosquito was first detected in India by Ross in 1898 (Carlton, 1938). Avian orders including Columbiformes, Galliformes, and Passeriformes are highly susceptible to *Plasmodium* spp., while Struthioniformes, Coliiformes, and Trogoniformes are resistant (Valkiūnas et al., 2005; Martinsen et al., 2008). *Plasmodium* sporozoites are transmitted to the avian hosts through the salivary glands of *Culicinae*, *Coquillettidia*, and *Anophelinae* mosquitoes (Njabo et al., 2011). Schizonts present in the macrophages and fibroblasts develop into merozoites in the hepatocytes, and then finally to gametes in the erythrocytes (Campbell, 1995). Both *Plasmodium* (*P.*) *gallinaceum* and *P. juxtanucleare* (Bisseru and Lim, 1971) and *P. vaughani* (Ludin et al., 1994) were isolated from crows, *P. formosanum* from White-breasted Waterhens (Yap et al., 1986), and an unidentified *Plasmodium* spp. from the Mountain Fulvetta (Paperna et al., 2008) in Malaysia. Therefore, wild waterfowl and wetland birds showed high rates of *Plasmodium* spp. infections because of their proximity to the insect vectors along waterways and tall reed beds.

The pathogenicity of *Plasmodium* in avian hosts usually varies during acute and chronic infections (Atkinson et al., 1995; Palinauskas et al., 2011). Affected birds may show no apparent clinical signs, while others show hepatomegaly with necrosis, fatty liver, splenomegaly, pericardial effusion and hydropericardium, nephritis, edematous lungs, occlusion of the brain capillaries, and hemorrhagic conjunctivitis (Omar and Lim, 1962; Ishtiaq et al., 2012; Dimitrov et al., 2015). Moreover, *Plasmodium* causing malaria induces pale watery blood, numerous immature erythrocytes, hemolytic and acute anemia, lymphocytosis, leukocytosis, hypoalbuminemia, diffuse areas of extramedullary erythropoiesis in the liver and kidney, and hemoglobinuria (Atkinson et al., 2000; William, 2005; Ferrell et al., 2007). Experimental infection of native Hawaiian forest birds with *P. relictum* revealed a reduction of feed intake and body weight as well as deaths due to anemia-associated-erythrocyte parasitemia (Atkinson et al., 1995). For human health considerations, *Plasmodium* spp. inducing avian malaria are closely related to the malarial parasites of humans, but they are not able to infect people.

2.3. *Haemoproteus* spp.

Most of avian species in almost all continents could be infected with *Haemoproteus* spp., however, very low incidence of these types are detected in Antarctica due to the absence of their vectors (Valkiūnas et al., 2005). *Haemoproteus* spp. may be transmitted by biting midges or *Culicoides* (*Ceratopogonidae*) and louse (*Hippoboscidae*) flies (Valkiūnas, 2005). *Haemoproteus* spp. have been identified in different avian species of forests (Paperna et al., 2008), pigeons (Al-Janabi et al.,

1980), doves (Amin-Babjee and Lee, 1992), and crows (Amin-Babjee et al., 1993; Ludin et al., 1994). Seven *Haemoproteus* (H.) spp. including *H. columbae*, *H. sacharovi*, *H. maccallumi*, H. melopeliae, *H. turtur*, H. perise, and *H. palumbis* have been detected in Columbids (Adriano and Cordeiro, 2001). However, *H. columbae* is considered the most common type that affected pigeons (Gülanber et al., 2002; Senlik et al., 2005; Youssefi and Rahimi, 2011; Al-Barwari and Saeed, 2012) and *H. nettionis* occurred in 56% of the northern wood ducks in the Atlantic Flyway (Thul et al., 1980). For the first time, *H. enucleator* was reported in red jungle fowl in China (Li et al., 2022). Moreover, a novel type of *Haemoproteus* spp. has been detected in Penguins in southwest Australia (Cannell et al., 2013).

Infections with *Haemoproteus* spp. have been associated with muscle affection, hepatomegaly, and splenomegaly (Atkinson and Forrester, 1987; Cardona et al., 2002). Moreover, hepatic hemorrhage, hemocoelom, and sudden death could also be observed in passerine birds (Donovan et al., 2008). Under natural or experimental conditions, H. meleagridis infection could be accompanied by muscle pathology in turkeys (Atkinson et al., 1988). The scarcity of studies on *Haemoproteus* infections in commercial poultry may be attributed to the difficulties in differentiating this parasite from *Plasmodium* during microscopic examination (Atkinson et al., 2009). Moreover, the pathogenesis of *Haemoproteus* infections in birds is still well not understood (Atkinson et al., 2009).

2.4. Other avian haemosporidian parasites

Despite *Trypanosoma* spp. having low pathological effects on avian hosts (Saif et al., 2008), *Trypanosoma* (*T.*) *avium*, *T. gallinarum*, *T. numidae*, and *T. calmetti* have been detected in different hosts (Saif et al., 2008). In Malaysia, *Trypanosomes* spp. have been found in Red-Jungle fowls and commercial poultry (Dissanaike and Fernando, 1974). Filarial nematodes of the genus *Pelecitus* (Dissanaike and Fernando, 1974), Cardiofilaria (Mak et al., 1984; Lee and Amin-Babjee; 1986; Amin-Babjee et al., 1993), and Lemdana (Amin-Babjee et al., 1985; Lee et al., 1989) have been demonstrated in commercial chickens, Red-Jungle fowls, crows, and spotted doves.

3. Incidence and distribution

Avian haemosporidian affections are genetically diverse (Ishtiaq et al., 2012; Padilla et al., 2017; Nourani et al., 2022). Infections with blood protozoon parasites have been reported in many countries all over the world, particularly those of high-temperature climates and vector activities. The distribution of blood parasites relies on host-parasite (Knowles et al., 2011) and vector-parasite (Carlson et al., 2015) compatibilities, mosquito feeding behavior (Medeiros et al., 2015), and climatic conditions (Garamszegi, 2011). The temperature, relative humidity, and rainfall reflect the numbers and activities of their insect vectors (Zamora-Vilchis et al., 2012). The broad host susceptibility to haemoprotozoan may increase the transmission rate and the prevalence of the parasites in numerous avian species (Bensch et al., 2009). Table 1 shows the incidence of avian haemosporidian parasites in different countries, from 1991 to 2023.

Country	Incidence in avian spp.	Reference
Nigeria	*Plasmodium* spp. were recognized in 48/150 (32%), *Leucocytozoon* spp. accounted for 30 (20%), while *Haemoproteus* spp. were identified in 2 (1.3%) of chickens' samples. In addition, mixed infection with *Plasmodium* spp. and *Leucocytozoon* spp. were detected in 14 (9.33%), but *Leucocytozoon* spp. and *Haemoproteus* spp. were demonstrated in 4 (2.67%) of samples.	Sadiq et al. (2003)
	Haemoproteus spp. (2.2%) and *Plasmodium* spp. (0.8%) were identified in the blood samples of pigeons, while *Plasmodium* spp. (5.8%) and *Haemoproteus* spp. (0.1%) detected in turkeys' samples.	George et al. (2004)
	The infection rate of *Plasmodium* spp. in pigeons was 3.0%.	Bui et al. (2005)
	The prevalence rate of *Plasmodium* spp. in 575 chickens and Guinea fowls was 9.4 %.	Igbokwe et al. (2008)
	Out of 250 pigeons, *H. columbae*, *Leucocytozoon* spp., and *P. relictum* were the protozoan parasites encountered with 49.2, 15.6, 6.4, and 0.8% prevalence, respectively.	Natala et al. (2009)
	Blood parasites were detected in 39/50 (78%) of pigeons. Infected birds showed *haemoproteus* (14%), *plasmodium* (30%), and *leucocytozoon* (4%) for the single infestation. However, double infestations showed *haemoproteus* and *plasmodium* (14%), *haemoproteus* and *leucocytozoon* (4%), and *plasmodium* and *leucocytozoon*	Dadi-Mamud Mamud et al. (2011)

Country	Incidence in avian spp.	Reference
	(4%). Triple infestations were 8%.	
	A total of 218 blood films were made from the wild (116) and domesticated (102) representing 6 pigeons, 2 Singing cisticola, 2 Western grey plantain eaters, 2 Buffalo weavers, 5 Laughing doves, 26 Black-headed weavers, 43 Cut-throat finches, 5 Long-tailed glossy starlings, 24 Cordon bleu finches, 50 poultry chickens, 46 local chickens, 3 Negro finches, and 4 African mourning doves. *P. circumflexicum*, *P. gallinaceum*, and *H. columbae* were found. The occurrence frequencies were 19.56% for local chickens, 50% for pigeons, 13.95% for Cut-throat finches, 50% for Grey plantain eaters, 33.3% for Negro finches, and 0% for other birds. Overall, 6.89% of all the wild birds showed infestations against 11.7% in domestic birds.	Karamba et al. (2012)
	Of 200 commercial and free-range chickens, 12% had haemoparasites and *P. gallinaceum* was identified with a prevalence of (12/0).	Usman et al. (2012)
	Haemoproteus spp., *Leucocytozoon* spp., *Plasmodium* spp., and microfilariae were detected in the blood samples of Weaver birds. Out of 30 birds, 22 (73.33%) showed presence of one or more haemoparasites. *Haemoproteus*, *Microfilariae*, *Leucocytozoon*, and *Plasmodium* spp. were found in 19 (63.33%), 10 (33.33%), 7 (23.33%), and in 5 (16.67%), respectively.	Olayemi et al. (2014)
	Out of 5040 of chickens and 560 of turkeys, 672 (12%) were infested with blood parasites, of which 448 (8.9%) were chickens and 224 (40%) turkeys. The prevalence rates of *Leucocytozoon* spp. were 448 (8.9%) in chickens and 224 (40%) of *Plasmodium* spp. in turkeys.	Opara et al. (2014)
	A total of 1820 chicken blood samples were examined for haemoparasites and the results showed a prevalence of 19.6% for 3 genera of haemoparasites in a single or mixed infections. *Plasmodium* spp. were the most prevalent (13.9%) followed by *Haemoproteus* (2.6%) and *Leucocytozoon* (0.4%) in single infection, but the prevalence of mixed infection with *Plasmodium* and *Haemoproteus* was 2.6%. Moreover, the prevalence rate was higher in male chickens (28.5%) than females (8.9%), and in adults (23.0%) than growers (11.0%). The prevalence rates were 39.3%, 12.5%, and 7.7% in the rainy, cold dry, and hot dry seasons, respectively.	Lawal et al. (2019)
	Out of 108 local chickens (49 males and 59 females) were examined. Females showed higher infection rate with blood parasites (53.1%) than males (46.9%). *Plasmodium* spp. were mostly found with a prevalence of 54.6%, in both males and females' chickens.	Mohammed et al. (2019)
	Two hundred and twenty blood samples representing local (95) and broiler (125) samples were examined. The overall prevalence rate of haemoparasites was 23.2%. In local and broiler chickens, the prevalence rates were 23.15% and 23.2%, respectively. *Plasmodium* spp., *Haemoproteus* spp., and *Leucocytozoon* spp. were encountered with *Plasmodium* spp. (23.5% and 21.6% in local and broiler chickens, respectively) showed the highest prevalence rate. The infection rate was in male (27.2%) and female (26.1%).	Ogbaje et al. (2019)
	Microscopic examination of blood samples revealed prevalence of 13.8% (290/2100) for blood parasites comprising of *Plasmodium* with 13.9% (198/2100) and *Haemoproteus* 2.4% (55/2100) as single infections. Mixed infection of *Plasmodium* and *Haemoproteus* had a prevalence of 1.8% (37/1820). Male chickens (9.9%) had a higher prevalence than female (4.0%). Besides, adults (10.4%) showed a higher prevalence than growers (3.4%), and prevalence was higher in the rainy (9.3%) than	Lawal et al. (2021)

Country	Incidence in avian spp.	Reference
	the dry (4.5%) season.	
	Of 345 birds (326 chickens and 19 guinea fowls), 315 blood samples showed haemoparasites that represented 91.30%. The prevalence of *Leucocytozoon* spp. was 42.90%, followed by *Plasmodium* spp. 33.62%. The However, the prevalence rates of *Haemoproteus* spp. and *Aegyptianella* spp. were 32.46% and 23.77% respectively.	Aiyedun et al. (2022)
Ghana	*Aegyptinella pullorum* and *P. juxtanucleare* have been detected in prevalence's of 9% and 27%, respectively from the blood of 100 chickens.	Poulsen et al. (2000)
Tanzania	*L. neavei* and *L. caulleryi* were found in the blood of guinea fowl and *L. schoutedeni* in chickens.	Fallis et al. (1973)
Malawi	The prevalence rate of blood parasites was 71%. Moreover, the indigenous scavenging chickens revealed the higher prevalence of infection (29.5 %) compared to the commercial and intensively managed chickens (0 %).	Njunga (2003)
Ethiopia	Of 384 chickens, the haemoparasite overall prevalence was 43.4% (167/384). Plasmodium spp., were predominant (18.2 %), followed by *Aegyptianella* (10.4%), *Leucocytozoon* (9.6%), and *Trypanosoma* spp. (0.5%).	Etisa et al. (2017)
Zimbabwe	Thirty two out of 100 (32%) chickens were infested with haemoparasites. The prevalence (%) of the parasites in young and adult chickens were: *Aegyptinella pullorum* (7; 6), *L. sabrazesi* (3; 1), *P. gallinaceum* (8; 6), and *T. avium* (2; 3).	Permin et al. (2002)
Kenya	Out of 144 chickens, 79.2% had haemoparasites, with 62.3% single and 37.7% mixed infestations. The prevalence of *P. gallinaceum* was (53.5%) followed by *L. schoutedeni* (52.1%), and *Hemoproteus* spp. (3.5%). Growers showed prevalence of 83.3% compared to 81.3% in adults, and 72.9% of chicks. The prevalence rates in males and female were 83.3% and 75.0%, respectively.	Mbuthia et al. (2011)
	Of the 144 chickens, 79.2% were infested with haemoparasites, with 62.3% single and 37.7% mixed blood parasites infestations. *P. gallinaceum* was the most prevalent (53.5%), followed by *L. schoutedeni* (52.1%), and *Hemoproteus* spp., (3.5%). The prevalence of haemoparasites in grower chickens was 83.3%, 81.3% in adults, and 72.9% in chicks. Moreover, the prevalence in male was 83.3%, while in females was 75.0%.	Sabuni et al. (2011)
Uganda	*Haemoproteus* and *Plasmodium* spp. were detected in the blood samples of 43 pigeons. The prevalence of *Haemoproteus* was 76.5%.	Dranzoa et al. (1999)
	Microscopic and PCR approaches were done on blood samples of 304 free-ranging chickens, 70 ducks, 14 turkeys, and 19 Guinea fowl. The results showed presence of *Haemoproteus* (17.25%, n=69), *Plasmodium* (22%, n=88), and *Leucocytozoon* (1.75%, n=7) in the sampled birds. The sequences from these genera were nested within their respective clades in a phylogenetic tree constructed using sequences from the MalAvi database.	Nakayima et al. (2019)
Uganda and Cameroon	Using of PCR and microscopy, out of 148 samples, 18.3% and 4.1% had *L. schoutedeni* and *T. gallinarum*, respectively. The phylogenetic analysis of the cytochrome *b* gene of *L. schoutedeni* identified 2 distinct lineages that were found at all 3 sampling locations in Uganda. The sequence divergence between these 2 lineages	Sehgal et al. (2006)

Country	Incidence in avian spp.	Reference
	is 1.5%. One of these lineages was also detected in Cameroon.	
South Africa	Out of 114 Guinea fowls, 98 (86%) revealed single or multiple infections of *Aegyptianella* spp., *L. neavei*, *P. circumflexum*, and *T. numidae*. The seasonal prevalence's of *Aegyptianella* spp., *H. pratasi*, and *L. neavei* were 42%, 49%, and 56%, respectively.	Earlé et al. (1991)
	Aegyptianella botuliformis and *Aegyptianella pullorum* were detected in the blood of Guinea fowls. *Argas* spp. were the vectors of the detected blood parasite.	Huchzermeyer et al. (1992)
	The incidence of avian malaria infections was 87.3% of seabirds.	Schultz and Whittington (2005)
Bangladesh	Sixty percent of the examined ducks were infected with *L. caulleryi* and *L. simondi*. Prevalence of *L. caulleryi* (54.67%), *while L. simondi* (5.33%). Prevalence of haemoprotozoa was higher in male (78.94%) than female ducks (53.57%).	Dey et al. (2008)
	The prevalence rates of *Plasmodium* spp. and *Leucocytozoon* spp. were 15.1% and 0.6%, respectively.	Elahi et al. (2014)
	A total of 213 pigeons blood samples were collected from Chittagong and Khulna districts. The results showed that mature and immature stages of *Haemoproteus* gametocytes were seen in 43.63% and 58.25% in Chittagong and Khulna district, respectively. The prevalence was almost similar in the areas of Khulna district (55.55 – 62.86%), whereas, a fluctuation observed in Chittagong district from 33.33 to 59.52%.	Islam et al. (2014)
	Thirty three out of 72 blood samples (45.8%) were positive for protozoa. *Leucocytozoon* spp. were 34.6% and 58.3% in chickens and ducks, respectively; but *Haemoproteus* spp. were 22.7% and *Leucocytozoon* spp. 22.7% in pigeons.	Momin et al. (2014)
	The prevalence rate of *Leucocytozoon* was 12% in chickens.	Nath et al. (2014)
	The examined 474 blood smears (266 chickens and 208 ducks) revealed presence of *Plasmodium* in 60 birds (12.7%), of which 35 were chickens (13.2%) and 25 were ducks (12.0%). *Leucocytozoon* spp. (10.5%) and *Plasmodium* spp. (2.1%) were identified. The high prevalence was 13.9% in adults, while it was 11.2% in young birds. Female (15.2%) was 1.46 times more susceptible than male (10.9%). Besides, the prevalence rates were 18.3%, 10%, and 9.3% in rainy, summer, and winter seasons, respectively.	Hasan et al. (2017)
	Out of 400 birds (200 chicken and 200 pigeons), 149 (37.3%) of birds had one or more haemoprotozoan parasites. Haemoprotozoa belonging to three genera were identified. Pigeons (40%) were more susceptible to haemoprotozoa than chicken (34.5%). About 118 birds (29.5%) showed single infection, while 31 birds (7.8%) showed mixed infections. The prevalence of blood protozoa in females (69.5%) than males (5%). In addition, the prevalence rate of haemoprotozoa was 60.6% in summer, 36.7% in rainy, and 23% winter seasons.	Nath and Bhuiyan (2017)
India	The prevalence of *H. columbae* was 18% in pigeons.	Senlik et al.

Country	Incidence in avian spp.	Reference
		(2005)
	Of 102 pigeons (44 nestlings and 58 adults), 2 blood-stained smears revealed presence of 47/05% of *H. columbae*.	Radfar et al. (2011)
Pakistan	Three blood samples out of 100 ones were identified with a prevalence rate of 29.3% for *P. juxtanucleare*, 15% for *Aegyptinella pullorum*, and 13% for *L. simond* in doves, ducks, pigeons, partridges, turkeys, and goose.	Sadaf et al. (2021)
Thailand	Out of 30 blood samples of Hill Mynahs, 3 birds were infected with *Haemoproteus* spp. Schizogony stage was found in the tissues, while gametogeny were the only stage detected in the red blood cells.	Archawaranon (2005)
	From 111 blood samples representing red-backed sea eagle, rock dove, spotted wood-owl, pheasant, peafowl, purple swamphen, spotted dove, common myna, tree sparrow, red-whiskered bulbul, and spotted owlet, 54 were positive (48.65%). Eighteen samples were positive for more than one species of haemoprotozoa. Blood parasites were *Microfilaria* 35.14% (39/111), *Haemoproteus* spp. 17.12% (19/111), *Leucocytozoon* spp. 8.11% (9/111), and *Trypanosoma* spp. 4.50% (5/111).	Buranapim et al. (2019)
	Out of 313 blood samples of chickens, the PCR assay showed *cyt*b gene of *L. sabrazesi* in 80.51% (252/313).	Chawengkirttikul et al. (2021)
Malaysia	Giemsa-stained blood smears of 728 Galliformes, Anseriformes, Phoenicopteriformes, Pelecaniformes and Gruiformes revealed presence of *Plasmodium* in a prevalence of 8.0%. The Anseriformes and Gruiformes showed infection rates (31.8-50.0%). The prevalence of *Plasmodium* was 2.7% in domestic poultry. Moreover, *L. sabrazesi* and *L. caulleryi* were limited to the Galliformes with infection rates of 0.7% and 0.5%, respectively. *Haemoproteus* was detected in domestic poultry and Red Jungle fowls with an average prevalence of 0.8%. *Trypanosomes* and *microfilaria* were only present in the village chickens and Red Jungle fowls, with a high *microfi laraemia* rate (19.0%) in Red Jungle fowls.	Gimba et al. (2014)
Indonesia	The microscopic examination and molecular sequencing of *cyt*b gene revealed presence of *Plasmodium* spp. and *L. caulleryi* in broiler chickens. The genetic distance between *L. caulleryi* taxa from various endemic areas is very close (<5%).	Suprihati and Yuniarti (2017)
Iran	Blood smears from 102 pigeons (44 nestlings and 58 adults), 47/05% were positive to *H. columbae*.	Radfar et al. (2012)
	Gametocytes of *H. columbae* were detected in 24% of blood smears of 100 healthy pigeons.	Samani et al. (2013)
	Of 220 pigeons, the prevalence rate of *H. columbae* was 23.18% (51/120).	Doosti et al. (2014)
	The stained blood samples of 150 pigeons showed presence of *Haemoproteus* gametocytes. The PCR sequence analysis of 17 samples revealed infection rate of 11.33% and all of samples belonged to *H. columbae*.	Tabaripour et al. (2017)
	Blood smears of 136 individuals belonged to 10 different families of songbirds were	Nourani et al.

Country	Incidence in avian spp.	Reference
	examined. Fifty-one passerine birds harbored *Haemoproteus* spp. besides, *Haemoproteus* spp. were detected in *Granativora bruniceps*, *Oenanthe pleschanka* species of birds.	(2018)
	About 11.64% (39/335) were infected with at least one parasite, especially *Haemoproteus* (32.6%; 23/335). The total prevalence rates for *Plasmodium*, *Haemoproteus*, and Leucocytozoon were 1.7%, and 2.9%, respectively. Besides, *Plasmodium* showed prevalence rate of 1.7% (6/335). Pigeons, hens, and ducks revealed prevalence rates of *Haemoproteus*, *Leucocytozoon*, and *Plasmodium* spp. at 1.7%, 6.8% and 2.9%, respectively.	Mirzaei et al. (2020)
	Molecular diagnosis of 152 avian hosts belonging to 17 species revealed presence of haemosporidian in an overall prevalence of 22.36%. *Haemoproteus* spp. were detected in pigeons, while *Plasmodium* spp. were found in Hooded crows and Carrion crow.	Nourani et al. (2021)
Egypt	The histopathological examination of the liver and lungs and the blood of 103 pigeon's revealed presence of different stages of *H. columbae* with a prevalence rate of 57.2%.	Hussein and Abdelrahim (2016)
	Blood smears of 100 diseased pigeon's revealed presence of *H. columbae* in an infection rate of 30%. It was more pronounced in males (35.71%) than in females (16.66%) and more in adults (57.14%) than in young (15.38%). The sequence of *H. columbae* showed 100% identity with other related *Haemoproteus* spp. in Brazil and United Kingdom.	Hala et al. (2020)
Iraq	Out of 128 samples, 2 samples represented *H. columbae* and *Plasmodium* spp. were detected in rock pigeons. The infection rates of gametocytes in red cells were 73.2 and 71.7% in males and female, respectively, but the schizonts were 31.7 and 41.5% in males and females, respectively	Al-Barwari and Saeed (2012)
	Out of 107 blood samples, the overall prevalence of haemosporidian spp. was 133 (78.2%) with 114 (85.7%) single and 19 (14.3%) mixed genera infections. The prevalence of *Plasmodium* spp. was (52.6%) followed by *Haemoproteus* spp. (19.5 %), and then *Leucocytozoon* spp. (13.5%).	Abdullah (2013)
	Out of 95 pigeon blood samples, 28 (29.47%) showed *Haemoproteus* spp.	Abed et al. (2014)
	Out of 50 chickens, 38 were positive for blood parasites high prevalence (76%). Birds were infested with 3 genera (*Plasmodium* spp., *Heamoproteus* spp., and *Leucocytozoon* spp.). Mixed infection with 2 haemoparasites (*Plasmodium* spp. and *Heamoproteus* spp.) were most prevalent (47.4%) than the triple ones (*Plasmodium* spp., *Heamoproteus* spp., and *Leucocytozoon* spp.) (36.8%) or others single haemoparasites infection. Single infection with *Heamoproteus* spp. was higher (13.2%) than *Plasmodium* spp. (2.6%) or *Leucocytozoon* spp. 0 (0%). Female chickens were more infected (97%) than males (3%).	Hasson (2015)
	A total of 234 birds including; 129 doves (56 males and 73 females) and 105 pigeons (59 males and 46 females) were examined. The only parasite that had been found was *H. columbae*. In doves, 14/129 showed total infection rate of 10.85% [7 (12.50%) males and 7 (9.58%) females]. However, 11/105 pigeons revealed infection rate of 10.48% [6 (10.17%) males and 5 (10.87%) females].	Wahhab et al. (2017)

Country	Incidence in avian spp.	Reference
	Of 140 sample of pigeons, the detected haemoparasites were *Haemoproteus* spp. (28.20%), followed by *Plasmodium* spp. (26.92%), and *Leucocytozoon* spp. (11.53%).	Abdullah et al. (2018)
	Leucocytozoon spp. 4 (5.5%) and *Haemoproteus* spp. 2 (2.8%) were detected in the blood smears of 74 pigeons.	Ul-Jabbar et al. (2019)
Turkey	A total of 200 wild pigeons, 114 showed infestations with *H. columbae* in 57% (114/200) and no other blood parasites were detected.	Gilik et al. (2001)
	Out of 118 pigeons, 43.2% were found to be infested with *H. columbae* and 17.8% to be infested with *Pseudolynchia canariensis*.	Gülanber et al. (2002)
	A total of 23 (%13.2) of 173 pigeons showed *Haemoproteus* spp. infestations. This parasite was found in 73.9% and 26.1% of pigeons over and under 1-year-old, respectively. Moreover, it was detected in females 56.2% (13/23) and in males (10/23) 43.4%.	Sürsal et al. (2017)
Brazil	Examination of 166 blood samples of passerine birds belonging to 46 species and 17 families showed that 11 birds (6.6%) were hosts for *Microfilariae*.	Silveira et al. (2010)
	Out of 925 birds, 15.8% in 11 families, were infected by at least one parasite genus, especially *Muscicapidae* and *Conopophagidae* in rates of 28.3% and 25%, respectively. Among the 146 positive birds, *Plasmodium* spp. were found in all bird families with a prevalence rate (54.8%). *Trypanosoma*, *Haemoproteus*, and *Microfilaria* showed prevalence rates of 23.3%, 23.3%, and 2.1%, respectively.	Sebaio et al. (2012)
Costa Rica	*Haemoproteus* spp. and Microfilariae were found in the examined 248 blood samples and 114 birds, respectively. The prevalence of *Haemoproteus* spp. was 0.8% and 4.4% in Hitoy Cerere and Barbilla, respectively, However, the prevalence *Microfilariae* was 8.1% and 3.5%, respectively.	Benedikt et al. (2009)
Colombia	A total of 315 birds including 75 species (23 families) showed that 50 birds (15.9%) had blood parasites. *Microfilariae* were the most common blood parasites, followed by *Haemoproteus*, *Plasmodium*, and *Trypanosoma* spp.	Rodriguez and Matta (2001)
	Blood samples collected from 302 wild and domesticated birds (75 species, 24 families) revealed presence of 28 individuals of 16 species (9.3% of all birds) infected with parasites of at least one genus. *Plasmodium* spp. accounted for 5.6% of the infections, followed by *Haemoproteus* spp. (2.6%), *Leucocytozoon* spp. (0.3%), and unidentified *Microfilariae* (1.0%).	Londono et al. (2007)
Germany	The prevalence rate of blood parasites in 1149 birds was 11% (adult birds 18%, immature birds 16%, and nestlings 4%). Among the Falconiformes 11% of 976 birds were infected, and 13% of 173 Strigiformes. Out of 17 falconiform spp., 9 were positive whereas the Eurasian buzzard showed the highest prevalence for haematozoa; i.e. *L. toddi* (31%), the highest prevalence (25%) for *Haemoproteus* spp. was found in the hobby. The tawny owl showed a highest prevalence with *H. syrnii* (22%). In the one pygmy owl, *T. avium* and *P. fallax* were found. The white-tailed sea eagle was a host of *L. toddy*.	Krone et al. (2001)
Italy	Out of 51 pigeons, 15 had *Haemoproteus/Plasmodium* spp. and 8 for *Leucocytozoon* spp. The DNA sequencing of *Leucocytozoon* spp. revealed 6	Scaglione et al. (2015)

Country	Incidence in avian spp.	Reference
	different lineages in pigeons, and 1 of *Haemoproteus* and *Plasmodium,* respectively.	
China	Out of 728 wild birds, the overall prevalence rate of *Plasmodium* and *Haemoproteus* was 29.5%, with 22% (*Haemoproteus*) and 7.8% (*Plasmodium*). Seventy-nine mitochondrial lineages including 25 from *Plasmodium* and 54 from *Haemoproteus* were characterized.	Zhang et al. (2014)
	Blood samples of 123 cranes were tested using PCR-based and microscopic examination. *Plasmodium*, *Haemoproteus*, and *Leucocytozoon* were detected. Malaria spp. were reported in 83% of all cases. *P. relictum* was the most prevalent parasite. However, co-infection of Plasmodium and Leucocytozoon spp. were also detected.	Jia et al. (2018)
Japan	The nested PCR of *cyt*b genes of from 415 wild birds revealed that 62 out of 415 (14.9%) were positive for haematozoa. The infection rates of *Leucocytozoon* were found among several forest species of birds (*Parus* ater, 64.3%; *Parus* montanus, 81.8%).	Imura et al. (2012)
United States of America	The amplified gene sequences revealed presence of *Plasmodium* spp., *Haemoproteus* spp., and *Leucocytozoon* spp. in the liver tissues of dead juvenile lesser flamingos, green jays, and Montezuma oropendolas	Ferrell et al. (2007)
Louisiana	Out of 935 individuals of 19 migrant and resident bird, 320 (34.2%) encountered hematozoa. The prevalence rates were *Haemoproteus* spp. 22.8%, *Trypanosoma* spp. 6.9%, unidentified *microfilariae* 5.0%, *Plasmodium* spp. 3.4%, and *Leucocytozoon* spp. 1.3%.	Garvin et al. (1993)
Bulgaria	*P. relictum, P. vaughani,* and *P. polare*, as well as *L. fringillinarum, L. majoris, L. dubreuili, L. eurystomi, L. danilewskyi*, and *L. bennetti* were found in the blood of 1332 The prevalence of the birds infested by *Plasmodium* was 6.2% as the parasites was detected in 82 birds (26 passerines). The highest prevalence of *Plasmodium* 18.5% (n=65) was detected in the family Fringillidae. A high rate was found in Passeridae: 18.3% (n=71), Turdidae: 11.2% (n=98) and Paridae: 10.3% (n=68). Besides, *Leucocytozoon* was detected in 17 wild birds from 9 species (n=1332) in a total prevalence rate of 1.3%.	Shurunlikov and Golemanksy (2003)
Queensland	A total of 3059 birds represented 40 families, 102 genera and 133 species were examined. The results demonstrated 350 (11.4%) positive to one or more species of haematozoa. *Leucocytozoon* (51.1% of infected birds), followed by *Haemoproteus* (31.4%), and *Plasmodium* spp. (10.9%).	Adlard et al. (2004)
Spain	*P. relicturn* and *Babesia fnigilegica* were detected in the blood samples of red-billed choughs.	Blanco et al. (1997)
Canada	Out of 510 ducks of 7 species, 76% were parasitized by one or more haematozoa. *L. simondi* was found in 91%, while haemoproteids in 11% of the infected ducks.	Bennett et al. (1991)

Table 1 – The incidence of avian haemosporidian parasites in different countries (1991-2023).

4. Laboratory diagnosis

The different developmental stages of the haemoparasites could be microscopically detected in blood or tissue smears after staining with Giemsa (Valkiūnas, 2005). The gametocytes are seen in stained blood films, while schizonts are detected in tissue

sections. However, the microscopic examination is insufficiently sensitive to detect the slight or early parasitism with a low number of sporozoites or gametophytes as in the case of *Leucocytozoon* spp. infections. Thus, the possibility of a false-negative diagnosis by this method is common (Valkiūnas et al., 2005; Garamszegi 2010). The centrifugation of the blood samples facilitates the concentration and detection of the parasites in the buffy coat and this method is significantly better than the direct blood smear (Bennett, 1962). Further, the plasma layer over the buffy coat is rich in *Trypanosoma* and *Microfilariae* spp., while the stained buffy coat film is rich in *Haemoproteus* and *Leucocytozoon* spp. Besides, the diagnosis of blood parasites in dead birds could be achieved via the histopathological examinations of the affected organs or through the prepared tissue smears before formalin fixation.

The molecular diagnostic techniques of amplification and sequencing of DNA or RNA are also useful, potential, and sensitive to detect the different stages of parasites in the blood or tissues even when the blood smears are negative (Palinauskas et al., 2013; Valkiūnas et al., 2014). However, some reports have shown that microscopic and molecular identifications have the same sensitivities for detecting avian haemoparasites (Valkiūnas et al., 2008, 2009). The PCR assay is regarded as an accurate and easy as well a rapid approach to investigate the presence of some blood parasites such as *Leucocytozoon* spp., *Plasmodium* spp., and *Haemoproteus* spp. (Hellgren et al., 2004). Gq et al. (2003) considered PCR as a special and sensitive test that shows no cross-reaction between *L. caulleryi* and other protozoon parasites, besides it can detect the lowest DNA concentration of the parasite in the tissues. The molecular-based detection of avian blood parasites usually depends on the mitochondrial genes (mtDNA) and the genomic markers that have been developed in the phylogeny of *Plasmodium* and related haemoprotozoon (Martinsen et al., 2008; Braga et al., 2011). Moreover, the molecular detection of a mitochondrial cytochrome b (*cytb*) gene could be a reliable, highly sensitive, and specific method of diagnosis, particularly in cases with false-negative blood smear results (Ortego and Cordero, 2009; Ramey et al., 2012; Suprihati and Yuniarti, 2017). By the amplification of a 478 bp fragment from the *cytb* gene, 6 *Haemoproteus* and two *Plasmodium* lineages were identified in the biting midges and the blood of 123 bird's spp. (Ferraguti et al., 2013).

5. Prevention and control

The adoption of modern intensive poultry production programs could reduce the incidences of parasitic infections. Moreover, the implementation of specific eradication measures for arthropod vectors could alleviate the possibility of parasite transmission (Piersma, 1997). Despite the employment of intensive control and management measures, few interventions have been directed toward managing infections in free-ranging domestic birds (Wong et al., 1998).

Antiparasitic compounds such as clopidol, primaquine, ketotifen, clomipramine hydrochloride, desipramine hydrochloride, sulfaquinoxaline, and ormetoprim combinations, halofuginone polys-styrene sulfonate, and pyrimethamine could be used for the treatment of blood parasites such as *Leucocytozoon* spp. (Kohne and Jones, 1975; Tanabe et al., 1985 and 1986). Primaquine is a member of the 8-aminoquinoline compounds that are effectively used to inhibit the sexual stages of some parasites such as *Plasmodium* spp. (Ashley et al., 2014) and *Leucocytozoon* spp. (Merino et al., 2000; Zhao et al., 2016). Pyrimethamine is used to control the asexual stages of the parasite in the blood (Baird and Hoffman, 2004; Baird, 2005). In addition, ketotifen, desipramine hydrochloride, and clomipramine hydrochloride are tricyclic antihistamines/antidepressants that have transmission-blocking activities against *Plasmodium* spp. inducing malaria. They inhibit the fertilization of gametocytes and the early development of oocysts in mosquitoes (Eastman et al., 2013). The gametocytocidal and transmission-blocking activities of artesunate in a *P. gallinaceum*-avian model were successfully evaluated (Kumnuan et al., 2013). Aminoguanidine, an inhibitor of inducible nitric oxide synthase, could treat *P. gallinaceum*-infected chickens in terms of increasing the survival rate, thrombocytopenia, and reducing anemia and hemozoin levels in the spleen and liver (de Macchi et al., 2013). However, *L. simondi* was not affected by paludrine, atebrin, and sulphamerazine treatments in ducklings (Fallis, 1948). Zhao et al. (2014) demonstrated that gametocytaemia of *L. sabrazesi* in blood samples of infested chickens showed 'relapse' or persistence of low-level for 4–5 months, which could be useful as an *in-vivo* model for the evaluation of the drug against liver stages of the parasite.

6. Conclusion

The present study brings an update on the incidence, distribution, and diversity of avian haemoparasites worldwide. The constant monitoring of the occurrence of avian haemoparasites in domestic poultry and wild migratory birds is required to reduce the risks of potential outbreaks. This could affect the international poultry industry as well as disrupt fragile wild bird populations.

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