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Optimizing the health of broilers

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1 Introduction

The broiler sector keeps growing in most countries worldwide at an average annual rate of 3.4% from 2009 to 2019 (IndexBox, 2021). Global broiler production reached 137 million tons of meat in 2020 (IndexMundi, 2021) (Fig. 1). Broiler meat is still one of the most well-accepted and affordable animal protein sources in all markets. In 2019, the highest levels of poultry meat per capita consumption were observed in Malaysia (63 kg per person), the United States (58 kg per person), and Brazil (57 kg per person). But, the highest volumes of poultry consumption were in China (20 M tons), the United States (19 M tons), and Brazil (12 M tons), compiling a 40% share of global consumption (Berkhout, 2020). The FAO has forecasted that poultry meat will decelerate with a compound annual growth rate of 2.3% between 2019 and 2030. Thus, it is projected that the poultry meat market worldwide will reach 166 M tons by 2030 (FAO, 2003). The top three broiler producers in the world continue to be the United States (23 M tons), China (20 M tons), and Brazil (16 M tons), with a combined 45% share of global production. They were followed by the 27 countries of the European Union, the Russian Federation, and India. The top five broiler-producing countries have accounted for almost 59% of global broiler production in the past 5 years.

Broiler production systems have been adapting to consumer demands related to the size and weight of birds, the final products required, food safety issues, welfare concerns, environmental impact, use of antibiotics, and other

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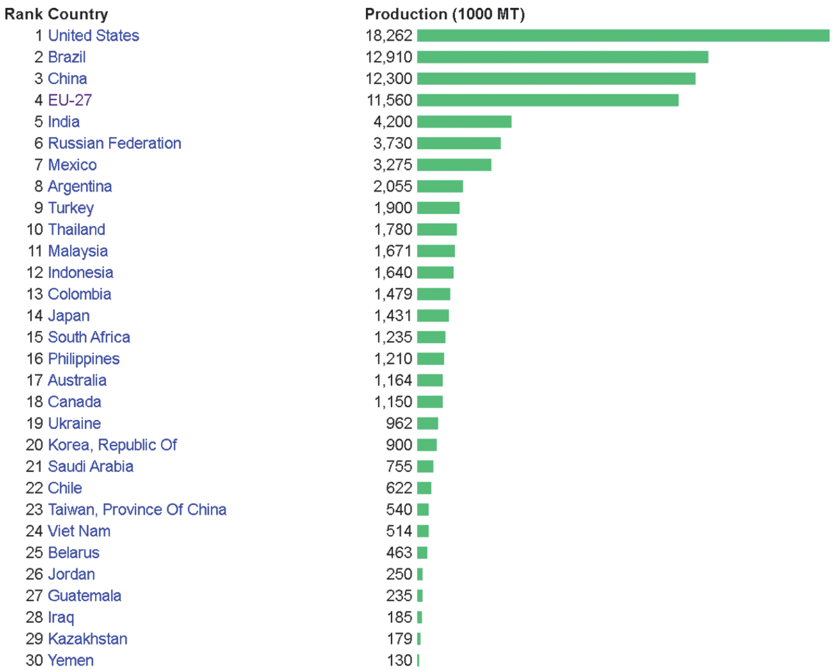

Figure 1 Estimated broiler production in the top 30 country producers in thousands of MT during 2020. (https://www.indexmundi.com/agriculture/?commodity=broiler-meat&graph=production).

related problems. The necessary changes in the production systems to meet these market demands represent some challenges. As the broiler industry develops, some health issues have become significant concerns with emerging and re-emerging diseases (Hafez and Attia, 2020). Despite using similar genetics worldwide, the infrastructural and organizational biosecurity, the technological level of housing, and environmental control vary greatly (Gelaude et al., 2014; Van Limbergen et al., 2018). Consequently, disease incidence, prevalence, and mortality rates fluctuate among countries and regions. The resources lost in mortality, disease prevention, nutritional and management interventions, carcass defects, and condemnations are considerable. Optimizing broiler health is a top priority for this industry due to the high cost of the major diseases, impacts on welfare, condemnations, and food safety issues at the processing plant (Jones et al., 2019; Blake et al., 2020). Control of broiler diseases has been demanding for several countries. For example, a recent study (Swidan et al., 2020) indicated that the losses due to mortalities resulted mainly from avian influenza (AI), Newcastle disease (ND), Gumboro, and coccidiosis diseases between 2008 and 2019 constituted about 52% of the total income from animal production in Egypt.

This chapter will present the critical infectious disease challenges faced by the top five broiler-producing countries. The current and future strategies to control these diseases will be discussed. These strategies include biosecurity, vaccination, surveillance, diagnostics, environmental management, nutritional interventions, and genetic selection. In addition, the potential strategies to enhance and optimize resistance to infectious diseases will be discussed while reducing the reliance on antibiotics or only on vaccination.

2 Key infectious disease challenges faced by broilers around the world

The disease challenges that broilers face change according to the type of housing and level of environmental control, weather conditions, poultry population density, endemic diseases in the area, final body weight, downtime between flocks, reuse of litter, water quality, diet composition and feed additives, health management plans, and biosecurity level, among other factors (Gaucher et al., 2015; Luyckx et al., 2015; Van Limbergen et al., 2018; Smith, 2019; Fancher et al., 2020; Abioja and Abiona, 2020; Van Limbergen et al., 2020; Swelum et al., 2021). The ranking of broiler diseases varies from country to country and within countries from region to region or company to company. There are major concerns around the world to preserve the food safety of poultry meat. Consequently, the prevention of diseases and contamination of meat and other edible poultry products caused by *Salmonella* and *Campylobacter* spp. are always top priorities due to the zoonotic implications (Hafez and Attia, 2020). This topic will be covered in other chapters and consequently will not be covered here. However, there are good sources of information to seek strategies to control *Salmonella* (Gast and Porter, 2020), *Campylobacter* (Zhang and Sahin, 2020), and other pathogens related to food safety.

With the fantastic collaboration of veterinarian colleagues, poultry scientists, producers, managers, and diverse experts located in the top broiler-producing countries or production areas globally, this chapter summarizes their informed opinion about the ranking of current broiler diseases. These rankings illustrate how specific disease occurrences may change depending on the production system used. These examples also help to discuss local challenges where they are more relevant. The broiler disease rankings were organized according to what experts surveyed and considered important in 2020, but data since 2017 are presented for the four bigger broiler producer countries. Thus, readers can conclude which are the critical points of control in each production system to minimize the incidence of diseases and optimize health. For the sake of brevity, only the most common diseases will be commented on for each country, but the complete list obtained in each country may serve as a future reference, and keep in mind that other health challenges must be addressed.

2.1 United States

In the United States, the Association of Veterinarians in Broiler Production (AVBP) produces an annual ranking of major broiler diseases and significant concerns of the industry included within the Committee on Poultry and other Avian Species of the United States Animal Health Association (USAHA, 2021). The AVBP ranking of broiler diseases during the past 4 years is presented in Table 1. This ranking indicates that coccidiosis, necrotic enteritis (NE), chick quality and early mortality, infectious bronchitis virus (IBV), and gangrenous dermatitis have been among the five most common diseases.

Intestinal diseases related to coccidia infection, dysbacteriosis, and NE have been the major challenges in the past 4 years. One factor could be the common utilization of reused litter in broiler houses generally for more than a year in several flocks. However, the greater relevance of gut health issues could be due to the rapid increase of antibiotic-free production. Currently,

Table 1 Broiler disease ranking in the United States from 2017 to 2020

Infectious disease category	Ranking			
Year	2017	2018	2019	2020
Coccidiosis	1	1	1	1
Necrotic enteritis	2	2	2	2
Chick quality and early mortality	4	3	3	3
Infectious bronchitis, IBV, respiratory	3	4	4	4
Gangrenous dermatitis	6	6	5	5
Novel reovirus	9	7	6	6
Bacterial osteomyelitis of the legs	11	8	8	7
General polyserositis – *Escherichia coli*	10	12	7	8
Infectious laryngotracheitis (ILT)	5	5	9	9
Infectious bursal disease	12	11	10	10
Vertebral osteomyelitis/kinky back	14	13	11	11
Infectious bronchitis, IBV, nephropathogenic	16	14	12	12
Histomoniasis	13	10	14	13
Avian influenza (AI)	7	9	13	14
Mycoplasma	15	15	15	15
Cholera			16	16
Newcastle disease (ND)		16	17	17
Marek's disease	17	17		

Source: Opinion of the Association of Veterinarians in Broiler Production (AVBP) included in the annual report of the United States Animal Health Association (USAHA), compiled and organized by Oviedo-Rondón (2019).

over 60% of the broilers in the United States do not receive growth-promoting antibiotics, and a growing percentage will meet requirements for no antibiotics ever programs (Smith, 2019; Fancher et al., 2020). In 2018, less than 8% of broilers were raised with the full spectrum of any feed antibiotics approved by the FDA.

Less than 15% of the chicks received an antibiotic in the hatchery in 2018, down from about 90% in 2013. Consequently, chick early mortality frequently includes bacterial contamination. Under this production system, chick quality and early survival are the vital aspects of success (Smith, 2019). Chick quality is related to the good development of all organs and physiological systems, including the immune system during incubation. Therefore, hatchery infrastructure, maintenance, management, and low contamination are pivotal in broiler production. Other bacterial diseases like gangrenous dermatitis, bacterial osteomyelitis, general polyserositis caused by *Escherichia coli*, and vertebral osteomyelitis could be related to dysbacteriosis that facilitates these pathogenic commensal bacteria (Smith, 2019; Fancher et al., 2020).

The most common viral challenges are IBV (Jackwood and de Wit, 2020; Legnardi et al., 2020), novel reovirus, and infectious laryngotracheitis (ILT) (Maekawa et al., 2019). These diseases have become either endemic or seasonal in some regions of the leading broiler-producing states. In some areas, the high population density, decades of using live vaccines, ILT chicken embryo origin vaccines, and the consequent appearance of IBV variants contribute to this higher incidence.

2.2 China

The author compiled in Table 2 the opinions of poultry veterinarians and live production managers from China and the incidence of diseases diagnosed in private laboratories recorded by the three largest broiler producers. These data include only the production of white-feathered chickens comparable to those produced in other countries. However, the housing systems for these broilers are mainly in cages and slats. Therefore, this table also includes the percentage of positive flocks to each one of the diseases.

The reader can observe the changes in disease categories reported in China compared to the United States and other regions of the world. Housing systems and the use of antibiotics may influence these results. In China, three housing systems are used for white-feathered broilers: the net-flooring system (NFS), the normal cage system, and the high-standard cage system. The main difference between the two cage systems is whether they use automatic feces-scraping equipment. Farmers raising white-feathered broilers prefer the NFS and cage systems over the standard flooring system with litter (Xin et al., 2016; Anderson, 2017; Chen et al., 2020). These housing conditions bring disease

Table 2 Ranking of diseases observed in white-feathered broilers in China from 2017 to 2020

Year	2017		2018		2019		2020	
Infectious disease category	Ranking	Positive[a] %	Ranking	Positive[a] %	Ranking	Positive[a] %	Ranking	Positive[a] %
General *Escherichia coli*	1	30.80	1	35	2	14	1	56.60
Staphylococcus	6	3.80	3	10	1	18	2	14.50
Infectious bronchitis, IBV (nephropathogenic and respiratory)	4	7.70	5	5	4	10%	3	11.50
Salmonella spp			10	2	6	6	4	4.00
Avian influenza (AI; H9N2)	2	19.20	5	5	8	4	5	2.90
Fowl adenovirus infections	4	7.70	12	2	13	1	6	2.60
Mycoplasma synoviae (MS)	2	19.20	5	5	7	5	7	1.70
Chicken infectious anemia (CIA)			2	13	8	4	8	1.20
Avian leukosis			10	2	3	13	9	1.20
Marek's disease	6	3.80	4	7	5	9	10	0.70
Reticuloendotheliosis					13	1	11	0.60
AI (H5N1)					8	4	12	0.40
Infectious laryngotracheitis (ILT)			9	3	11	3	13	0.20
Newcastle disease (ND)	6	3.80	8	4	11	3	14	0.10
Avian reovirus			12	2				
Infections bursal disease	6	3.80	12	2				

Source: Poultry veterinarians and live production managers of the Republic of China.
[a]Percentage of positive flocks for a specific disease over the total evaluated in diagnostic laboratories of the largest three broiler integrator companies.

challenges different from those observed in flooring systems with litter or reused material common in other countries. In addition, the low contact of birds with excreta reduces the incidence of coccidiosis and NE.

In contrast, Chinese veterinarians and experts reported a high incidence of *E. coli* and *Staphylococcus* spp. infections that also have been described in publications (Xu et al., 2020). These are some of the most prevalent bacteria in the intestines and the skin of poultry and humans. If these groups of commensal bacteria and *Salmonella* spp., especially *Salmonella pullorum*, cause persistent diseases in broilers, subclinical dysbiosis could be one of the main unforeseen issues (Ducatelle et al., 2018). It is important to notice that in the opinion of Chinese veterinarians working with broiler production in flooring systems and also probably some yellow-feathered chickens, coccidiosis, NE, and mycoplasma are the top three diseases together with viral infections like ND, AI, IBV, infectious bursal disease, and ILT.

Regarding dysbacteriosis, it is necessary to consider the type of feed ingredients, feed processing, water quality, and feed additives used. The use of growth-promoting antibiotics in China was elevated in the past years (Krishnasamy et al., 2015; Schoenmakers, 2020). In 2013, China consumed nearly half the world's antibiotics, 162 000 tons, 52% administered to animals. These volumes raised concerns in the public and governmental institutions.

Krishnasamy et al. (2015) commented that coccidiostats and arsenicals were the most common antimicrobials used in Chinese poultry production by weight. However, macrolides, penicillins, and tetracyclines were also widely used, resulting in potential antimicrobial resistance (AMR) and public health. In 2020, Xu et al. reported that the misuse of antibiotics in medium- and small-sized farms is still high in some regions of China. These authors also indicated that amoxicillin, oxytetracycline, and ceftriaxone were the most commonly used antibiotics, while ofloxacin and norfloxacin were the second most common antibiotics employed. This report confirms that penicillin, tetracyclines, cephalosporins, fluoroquinolones, and quinolones utilized in human medicine were misused in poultry. As a result, China has had one of the highest frequencies of AMR in the world (Schoenmakers, 2020). For instance, colistin-resistant *E. coli* (CREC) infections in humans and animals have been widely reported in China (Wang et al., 2018).

The situation may be changing at this moment (Schoenmakers, 2020). In 2016, the Chinese government announced the National Action Plan to Combat AMR from Animal Resources (2017–2020). For example, colistin use in animal feed was banned on April 30, 2017. Consequently, colistin sulfate premix production decreased from 27 170 tons in 2015 to 2497 tons in 2018. A recent evaluation by Wang et al. (2020) of CREC and *mcr*-1 bacterial gene abundance, the bacterial marker for this AMR, from animals and humans between 2015 and 2019, indicated that after the ban, colistin residue in chicken farms decreased

96%, and the median relative abundance of *mcr*-1 per 16S RNA decreased 77%. The CREC identification went from 18.1% to 5%. However, clinical CREC infections in humans from 26 provinces and municipalities comprised 1.7% of *E. coli* infections in 2015–16 and only reduced to 1.3% in 2018–19. This data and other evidence indicate that AMR infections may persist in human and poultry populations for a few more years (Schoenmakers, 2020). This situation in China is a good example of how the problems related to antibiotic use may evolve in other countries that still are initiating this process.

The Ministry of Agriculture and Rural Affairs has pointed out Chinese medicine and probiotics as likely candidates for new product research among antibiotic substitutes. However, like in any other part of the world, plans for antibiotic substitution must also include improving chick quality, farm sanitation, biosecurity, enhancing drinking water and feed quality, integral programs of disease prevention, training about appropriate antibiotic use to farmers, and awareness of the risks of misusing them. Other key factors include educating farmers, veterinarians, and pharmacists in disease diagnostics, providing technological tools for faster and better diagnostics, restricting free availability, and enforcing the national regulations.

The IBV disease is also a key challenge for China's broiler industry like it is in almost the whole world. Both respiratory and nephropathogenic IBV strains are observed. The AI subtype H9N2 of low pathogenicity (LPAI) and the highly pathogenic subtype H5 (HPAI) occurrence is more common in China than in other countries (Parvin et al., 2020; Bo et al., 2021). Xu et al. (2020) also indicated that ILT and ND had been diagnosed in approximately 42% of 88 broiler farms surveyed in their study, which could mean a high incidence in some regions of China.

2.3 Brazil

The opinions of renowned Brazilian poultry veterinarians working in diverse integrations, vaccine companies, and diagnostic centers were compiled in Table 3. Currently, coccidiosis ranks again as the number one disease, and chick quality and early mortality are considered even more critical than nonspecific enteritis observed (Gazoni et al., 2020, 2021).

In surveys between 2012 and 2019, Gazoni et al. (2021) evaluated 13 648 broilers between 9 and 49 days of age in 13 Brazilian States. This group detected subclinical coccidiosis evaluated by microscopy due to *Eimeria maxima* in 34.8% of the flocks. In another study conducted between 2017 and 2018, the same group (Gazoni et al., 2020) observed *E. maxima* in 45% of mucosa scrapings in 32 broiler integrator companies. However, *Eimera acervulina* had the highest prevalence in macroscopic lesions, positively correlated with cellular desquamation, bedding ingestions, and feed passage. In addition,

Table 3 Ranking of broiler diseases in Brazil from 2017 to 2020

Disease category (infectious disease)	Ranking			
Year	2017	2018	2019	2020
Coccidiosis	1	1	1	1
Chick quality and early mortality	5	5	2	2
Enteritis (unspecific)	3	2	4	3
Infectious bronchitis, IBV (respiratory)	2	3	3	4
Escherichia coli (general polyserositis)	4	4	5	5
Mycoplasma (MG and MS)	6	8	7	6
Novel reovirus	9	10	8	7
Salmonellosis (*Salmonella pullorum* and *Salmonella gallinarum*)	8	7	6	8
Infectious bursal disease (IBD)	7	6	9	9
Infectious coryza	14	13	13	10
Infectious bronchitis, IBV (nephropathogenic)	11	9	10	11
Cholera	10	11	11	12
Bacterial osteomyelitis in legs	12	12	12	13
Infectious laryngotracheitis	17	17	16	14
Necrotic enteritis	16	16	15	15
Chicken infectious anemia (CIA)	13	14	14	16
Avian encephalomyelitis	15	15	17	17
Gangrenous dermatitis	18	18	18	18
Vertebral osteomyelitis	19	19	19	19
Marek's disease[a]	20	20	20	20
Histomoniasis[a]	21	21	21	21
Newcastle disease[b]	22	22	22	22

Source: Brazilian poultry veterinarian specialists.
[a]Extremely low incidence. Avian Influenza is still considered an exotic disease in Brazil.
[b]Latest outbreak limited to wild or backyard birds.

these studies identified factors that correlated with a reduction in intestinal health and negative effects on performance.

The fourth disease is the respiratory form of IBV (Colvero et al., 2015; Bande et al., 2017), and *E. coli* infection (Gonzalez and Cerqueira, 2019) is the fifth disease in this ranking. Colvero et al. (2015) calculated that IBV causes total losses of US$3563 per 1000 broiler breeders and $266.4 per 1000 broilers. There are several reports of multiple occurrences of outbreaks caused by IBV genotypes that differ (>25% divergent) from the Massachusetts type, which is the only type of live IB vaccine for vaccination in Brazil (Bande et al., 2017). Consequently, the economic losses could be attributed to poor vaccine protection (Colvero et al., 2015). This could be due to rapid mutations during replication of H120 and Ma5 viral strains used for vaccination in Brazil (Saraiva et al., 2018).

Mycoplasma infection is still the sixth most common disease (Reck et al., 2019). AI is still exotic in Brazil, and ND has occurred only in backyard flocks in the past decades. In Brazil, the housing, management, feed ingredients, feed additives, and the whole broiler production system are similar to those observed in the United States. Therefore, the critical disease challenges are very similar.

Brazil is the largest exporter of broiler meat globally, with a market share of almost 40%, exporting to over 150 countries. Consequently, broiler producers must meet Brazilian regulations and those from their main markets in China, Saudi Arabia, South Korea, the European Union, South Africa, and Japan. Some of these regulations include exporting products free of residues and even metabolites of antibiotics and coccidiostats. As a result, part of the Brazilian broiler production is antibiotic-free or has more extended withdrawal periods.

2.4 The European Union

The author used two sources of information to formulate a view of Europe's key infectious disease challenges. First, the author was given access to a disease prevalence data set of the Poultry Veterinary Study Group of the European Union (PVSGEU) and the most recent quarterly reports from the European Food Safety Authority related to AI (EFSA, 2021b).

The PVSGEU members are an informal group of poultry veterinarians from countries across the continent who meet twice each calendar year to share experiences on poultry disease, poultry welfare, and food safety issues in the poultry sector that have arisen during the previous 6 months. The PVSGEU has provided a summary document to the author of the trends in poultry disease incidence reported by the country members over the last two decades. However, this data set should be interpreted with caution. It is not an official record of the EU poultry disease incidence but reports individual veterinarians' views that can be influenced by various factors related to their work area.

The author has noted the following findings from the PVSGEU data set (Table 4). The use of antibiotic growth promotant in poultry diets was banned from January 1, 2006. However, despite the antibiotic ban, coccidiosis and NE do not feature the top three diseases of concern. Clostridium-associated diseases rank third, suggesting that overt NE is less of an issue for European poultry producers, but other clostridium-associated conditions are not uncommon. Together with leg problems, chick quality and early mortality are the two most important disease conditions that the PVSGEU encounter. This report probably reflects the complex etiology of these conditions and, therefore, why they

Table 4 Ranking of broiler diseases based on PVSGEU data set from 2017 to 2020

Infectious disease category	Ranking			
Year	2017	2018	2019	2020
Chick quality and early mortality	7	2	1	1
Leg problems	2	6	5	2
Clostridium	3	3	3	3
Enterococcus	4	4	1	3
Bacterial osteomyelitis of the legs (femoral head necrosis)	3	5	8	4
Enterococcus caecorum	5	8	4	4
Infectious bronchitis, respiratory	8	6	14	5
Escherichia coli infections	1	1	2	5
Dysbacteriosis	10	6	8	5
Necrotic enteritis	13	7	7	6
Marek's disease	10	14	15	6
Infectious bronchitis, IBV (nephropathogenic)	13	9	10	7
Coccidiosis	6	4	4	8
Infectious bursal disease	13	12	9	9
Campylobacter	8	6	6	9
Inclusion body hepatitis (IBH)	13	9	14	10
Gizzard erosion	10	10	13	11
Novel reovirus	14	13	11	12
Mycoplasma synoviae	11	11	16	12
Ruptured tendon	13	11	15	12
Avian influenza (H5N8) broilers	5			12
Eimeria necatrix	15	14	15	13
Vertebral osteomyelitis/kinky back	9	8	15	14
Enterococcus hirae	11	10	16	14
Gangrenous dermatitis	18		17	15
Mycoplasma gallisepticum	14	15	17	15
Avian encephalomyelitis	17	15	17	16
Infectious laryngotracheitis	11	14	15	17
Chicken anemia virus (CAV)	16	13	17	17
Black bone	17	16	17	18
Newcastle disease	17	16	18	

Source: Poultry Veterinarians Study Group from Europe (PVSGEU). Data were compiled and adapted from Oviedo-Rondón (2019).

continue to be reported. *Enterococcus* infections rank high in more recent years, which undoubtedly reflects the significant reduction in the use of therapeutic antibiotics in poultry production across the EU (Jung et al., 2018).

E. coli infections regularly rank high in the list, but this is unsurprising as *E.coli* is a common bacterial finding at postmortem examination in poultry (Nolan et al., 2020). Dysbacteriosis ranked fifth in 2020, but this is a syndromic condition related to intestinal integrity and stability that can be influenced by multiple factors, including feed ingredient quality, which often reflects feed pricing.

AI was not ranked high in the 2020 PVSGEU summary (Table 4). Still, the data set was collated 6 months before the 2020/2021 winter HPAI incursion and, therefore, the spike in case numbers related to the latest incursions. The author has collated the information about the HPAI status from the *EFSA Journal* quarterly reports, which are available online. According to *EFSA Journal* (2017), since 2005, at least 10 major incursions of HPAI H5 viruses through wild migratory waterbirds have occurred in Europe, almost one every year. The HPAI outbreak 2016–2017 affected 109 thousand birds categorized as chickens, which was only 3.9% of the total birds' population found positive for HPAI (*EFSA Journal*, 2017). The great majority of chicken cases were backyard flocks, breeders, and layers. Most of the outbreaks were reported in wild birds and domestic waterfowl (Foie Gras production).

From November 26, 2020, to May 31, 2021, 1247 cases had been reported in poultry, 65 detections in captive birds, and 2243 HPAI in wild birds (EFSA Report February–May, 2021). Until March 2020, most affected flocks had less than 1000 broilers, mainly backyard flocks with mixed species. But, between February 12 and April 30, 2021, 297 poultry farms and more than 10 million birds were affected only in Poland. Among 560 outbreaks in this second peak and short period, 98.4% were positive for HPAI subtype H5N8, six outbreaks were H5N1, and three outbreaks were H5N5. In these outbreaks, 35.2% of the poultry facilities had more than 10 000 birds, 18% had between 1000 and 10 000 birds, and 46.8% had less than 1000 birds.

Over 22.4 million birds have been affected, which is already eight-fold more than in the previous biggest outbreak that occurred between 2016 and 2017 (EFSA, 2017, 2021a). Like in the last epidemic, France has had 95.91% of the cases in domestic poultry, Germany has reported 83.05% of the cases in wild birds, but this time, Poland had 78.75% of the outbreaks in poultry. However, these reports also depend on the importance given in each country to wild bird surveillance. The risks for zoonosis are from very low to negligible, but monitoring is undergoing. No human infection with AI viruses has been identified until May 31, 2021, in the EU (EFSA, 2021b).

Biosecurity is crucial for AI control and all outdoor farming, movement of poultry should be minimized, and compulsory indoor confinement of free-range poultry must be implemented (EFSA, 2021a,b). The main issue with HPAI and even LPAI in Europe is the growing tendency for free-range poultry and outdoor farming (EFSA, 2021a,b). Under these conditions, domestic waterfowl get closer to migratory birds that bring viruses common in Asia in their migration cycles (EFSA, 2021a,b). Other aspects of current and future AI diagnosis, surveillance, epidemiology, and control are discussed in detail by Swayne et al. (2020).

2.5 Other countries

A survey was conducted with at least 12 poultry veterinarians from Russia, India, Colombia, and Chile to obtain their informed opinion of the most prevalent diseases in these countries. The results are presented in Table 5. The complex respiratory disease, *E. coli* infections, and IBV ranked high in almost all countries. However, AI is exotic in Colombia, and no cases have been observed in broilers in Chile.

Table 5 Ranking of broiler diseases in other countries in 2020

Infectious disease category	Russia	India	Colombia	Chile
Complex respiratory disease		1	1	
Escherichia coli	3	2	3	4
Infectious bronchitis (respiratory), IBV	1	5	2	5
Avian influenza	5	3	[a]	[a]
Coccidiosis	7	6	4	1
Dysbacteriosis	8	7	5	2
Infectious bursal disease	4	10	7	8
Newcastle disease (ND)[b]	9	4	8	11
Bacterial osteomyelitis of the legs	2		10	14
Mycoplasma	14		6	6
Necrotic enteritis	10	8	14	3
Infectious bronchitis (nephropathogenic)	6		12	12
Novel reovirus			13	7
Chick quality and early mortality	11	11	9	10
Infectious laryngotracheitis	12		11	9
Inclusion body hepatitis		9	15	
Vertebral osteomyelitis/kinky back	13		16	
Gangrenous dermatitis			17	13

[a] Avian influenza is considered an exotic disease in Colombia, and in Chile, no cases have been observed in broilers.
[b] Latest outbreaks are limited to wild or backyard birds.

AI is of great concern in India and Russia. India has had outbreaks of HPAI H5N8 since the end of 2020 in poultry and wild birds (EFSA Report February–May, 2021). Russia has had reports of H5N8. This time, seven poultry workers were infected in Russia with the subtype H5N8 presenting mild or no symptoms. These human infections were very unusual and required further precautions (*EFSA Journal*, 2021). Additionally, the wide expansion of H9N2 in Russia may be causing greater economic damage to poultry production than H5 and H7 subtypes that are generally more localized (Parvin et al., 2020). H9N2 viruses are also of greater concern for zoonosis due to their human receptor binding and risk of virus reassortant with human influenza (Peacock et al., 2019; Parvin et al., 2020).

Coccidiosis, non-specific dysbacteriosis, and NE are also important. Intestinal and respiratory health are again the main aspects to optimize broiler health independently of latitude, housing technologies, and environmental control capabilities. However, issues become worst when extreme weather conditions occur everywhere in the world.

3 Present and potential strategies to optimize control of infectious diseases

In the final section of this chapter, the current and future strategies for preventing and controlling the five most important broiler infectious diseases in the great majority of countries will be discussed. Disease prevention and control involve the following three interconnected processes: bioexclusion, surveillance, and biocontainment (Collett et al., 2020). The first step is limiting the challenge by biosecurity, sanitation, water and feed quality, and house environmental control. The second is enhancing resistance by immunization, immunomodulation, or genetic selection. The third is preventing the spread of diseases by boosting biosecurity and surveillance and practicing quarantine. These strategies include housing infrastructure, equipment maintenance, management, nutritional, immunological, and genetic selection factors that could be used to optimize broiler health.

Additionally, new technologies with potential benefits in prevention will be briefly discussed. The options to reduce dependence on antibiotics and reliance on only vaccination will be emphasized. Finally, this discussion will illustrate how other diseases could be addressed.

3.1 General strategies to optimize broiler health

3.1.1 A multifactoral approach

There is a global agreement that a multifactorial approach is required to prevent and control all infectious diseases (Williams, 2005; Oviedo-Rondón, 2019; Smith, 2019; Hafez and Attia, 2020; Jackwood and de Wit, 2020; Collett et al., 2020; Swelum et al., 2021). Diagnostics is key to identifying the exact etiology of the health issue to control. A variety of laboratory and field diagnostic techniques and tools are available for each broiler disease (Collett et al., 2020). However, the occurrence of a single disease caused only by one pathogen is not the most common case, and often, there are multiple factors and even pathogens involved (Smith, 2019; Collett et al., 2020).

Then, diagnostics, prevention, and control of infectious disease involve understanding the whole production system. The design of strategies to optimize health requires identifying and understanding the presenting illness and considering the big picture of other contributing diseases and influential aspects (Owen, 2017). In this way, we can articulate complete pathogenesis that indicates points of action for control and prevention. These diagnostic exercises require accurate and complete information that may integrate the disease *per se* and production over time (Owen, 2017). Many infectious diseases are subclinical and could be detected on the production records, meat inspection services at the processing plants, welfare audits, or monitoring systems (Huneau-Salaün et al., 2015).

Data analytics is becoming more vital to optimize broiler health, to summarize multiple environmental and performance parameters, and to detect trends, correlations, and causation (Collett et al., 2020). In diagnostics, the conventional microbiological and histological methods are being replaced by serology, mass spectroscopy (matrix-assisted laser desorption ionization time-of-flight mass spectrometry), polymerase chain reaction-based techniques, and other DNA techniques to detect pathogens. These techniques can also identify changes in the microbiome that may need to be modulated to achieve good results in the prevention. Diagnostic procedures are becoming more portable, rapid, sensitive, accurate, and cost affordable (Umesha and Manukumar, 2018). The development and adoption of these tools have good value to optimize health.

In the prevention and control of infectious diseases, biosecurity is the first line of defense and the most economical in the long term (Gelaude et al., 2014; Owen, 2017; Van Limbergen et al., 2018; Smith, 2019; Hafez and Attia, 2020). Van Limbergen et al. (2020) conducted a study with 2309 flocks from 358 broiler farms in 2016 to investigate the risk and protective factors that may affect health, performance, dead on arrival, and condemnation rates in conventional broiler farms. This study was conducted in seven EU member states that included Belgium, Cyprus, Finland, Greece, Poland, Spain, and the United Kingdom as a part of the EU-funded project PROHEALTH. The factors found to be significant in each case are summarized in Table 6 by their order of importance. It is essential to highlight the relevance of ventilation in the majority of the health aspects evaluated. It is also remarkable that intestinal

Table 6 Order of importance of factors associated with mortality live performance, dead on arrival, and condemnation rates in 2309 conventional broiler flocks from 358 broiler farms in 7 EU member states[a]

Independent variables	Mortality	Live performance	Dead on arrival	Condemnation rate
Litter quality[b]	1			
Neonatal septicemia[c]	2			
Ventilation type[d, e]	3	6		4
Farmer management activities	4	7		
Chick sex[f]		1		
Coccidiosis		2		
Necrotic enteritis		3		
Dysbacteriosis		4		
Light intensity adaptations[g]		5	2	
Daily growth rate			1	2
Type of drinker system[h]			3	1
Feed withdrawal time				3
House size				5
Septicemia after 7 days				6
Type of feed[i]		8		7

Source: Adapted from Van Limbergen et al. (2020).
[a] Only the statistically significant risk factors in the final models are presented.
[b] The reference used for floor quality was a floor in perfect conditions without cracks.
[c] This was only the case in tunnel-ventilated broiler houses.
[d] The reference used for the type of ventilation was roof ventilation.
[e] Interpreted as a trend, as it was not significant ($P > 0.05$).
[f] If only male chicks were housed, a higher EPI was present.
[g] The reference for light adaptation was dimming the light intensity.
[h] The reference used for drinking system was the nipple drinking system.
[i] Only the case when dysbacteriosis was absent in the flock.

health diseases were significant for live performance and involve water and feed factors.

3.1.2 Broiler housing

Proper house ventilation is critical to guarantee optimal temperatures and maintain air and litter quality (Dunlop et al., 2016). House ventilation is the primary management factor affected when weather conditions become extreme. Either heat or cold stress, often observed under extreme weather conditions, plays a vital role in several health and welfare issues (Das et al., 2011; Part et al., 2016; Saeed et al., 2019; Kpomasse et al., 2021). As global climate change circumstances become more frequent, broiler housing must be more prepared to deal with extreme conditions. Increased temperatures may increase cooling energy demand and reduce heating energy demand in broiler houses (Izar-Tenorio et al., 2020; Abioja and Abiona, 2020). However, these tendencies may change depending on season and location. Increasing the size of the houses and adding insulation may help mitigate the energy demand variability (Izar-Tenorio et al., 2020). Other strategies to ameliorate heat stress could be related to diet manipulations, use of phytochemicals, breeding for thermo-tolerant strains, and thermal conditioning during embryo development or early life (Das et al., 2011; He et al., 2018; Abioja and Abiona, 2020; Ncho et al., 2021).

3.1.3 Feed and water

At least 3 of the top 10 critical diseases for broilers worldwide are related to gut health. Coccidiosis and clostridiosis are frequently reported as the most common and costly (Jones et al., 2019). Control strategies for these intestinal diseases share common roots. The most successful nutritional and management plans have been discussed in previous publications (Williams, 2005; Yegani and Korver, 2008; Cowieson and Kluenter, 2019; Oviedo-Rondón, 2019; Smith, 2019). However, it is essential to emphasize the importance of monitoring water quality and implementing technologies to maintain it or improve it wherever is necessary (Barton, 1996; Watkins et al., 2005; Manning et al., 2007a,b; Abbas et al., 2008; Elsaidy et al., 2015; Jacobs et al., 2020). Distance monitoring with sensors of water pH, oxidation–reduction potential, temperature, and flow can help broiler growers to control water quality (Astill et al., 2020; Neethirajan, 2020).

Water is the primary nutrient ingested by broilers and sometimes the most variable among farms and even daily in a farm (Manning et al., 2007a,b; Williams et al., 2013; McCreery, 2015). Water line height, flow rates or water pressure, and drinker types may impact broiler water and feed consumption and consequently growth (Lott et al., 2001; Ipek et al., 2002; Brown, 2013; Quilumba et al., 2015). Additionally, water drinker management impacts relative humidity, ammonia concentration, and litter quality (Dunlop et al., 2016). High moisture in the house environment contributes to increasing not only *Eimeria* spp. and *Clostridium* spp. populations but also all kinds of microorganisms, including viruses and insects, which can negatively affect broiler health or propagate vectors for transmission to other locations.

Consequently, in most cases, water management has a more significant impact than any feed factor in gut health. Water properties may alter physicochemical conditions in the gastrointestinal tract, affect gut motility, digestion, and microbiota. Water alkalinity, magnesium, sulfates, nitrates, and nitrites have the most harmful effects (Barton, 1996; Abbas et al., 2008; Elsaidy et al., 2015). Water acidification with acetic acid at 3% in drinking water has been proven to be as or more effective under coccidia infection than amprolium to improve body weight gain, feed conversion, reduce lesion scores, and oocyst counts in broilers (Abbas et al., 2011).

Feed quality assurance is pivotal in gut health (Kiarie and Mills, 2019). However, quality can never be limited to optimizing nutrient utilization, reducing prevalent mycotoxins, reducing contamination and oxidation. Plant feed ingredients may contain numerous antinutritional factors, proteins, and fibers of difficult digestion by birds. The adverse effects of those feed components that alter digestibility, absorption, and even metabolism of nutrients can be effectively minimized by adequate pre-processing of feed ingredients during drying and storage, proper uniform particle size post-grinding, and proper temperature settings in the pelletization process (Lilly et al., 2011; Kiarie and Mills, 2019). In addition, feed hygienic status and efficacy of feed additives have significant effects on animal health and food safety. The addition of exogenous enzymes is another effective methodology to improve gut health. Enzymes improve digestion by mitigating the impact of antinutritional factors such as phytate, non-starch polysaccharides, proteins of difficult digestion, providing substrate for symbiotic bacteria, stimulating beneficial microbial fermentation, and modulating gut microbial communities (Keerqin et al., 2017; Cowieson and Kluenter, 2019).

3.1.4 Data and information for decision-makers

Data-driven technologies, modeling, smart sensors, machine vision, big data, and the internet of things may help to model and understand the epidemiological factors, predict the onset of infectious diseases, and improve the welfare and health of broilers (Brooks-Pollock et al., 2015; Astill et al., 2020; Li et al., 2020; Neethirajan, 2020). Sensoring data together with advanced data analytics techniques can provide early warnings for intervention to control diseases when they start and reduce the use of antimicrobials and anticoccidial drugs (Corkery et al., 2013).

Borgonovo et al. (2020) presented the development of a data-driven machine learning algorithm that uses specific critical values of volatile organic compounds in the air that are associated with abnormal levels of oocysts count at the early stage of coccidiosis. Applications of early detection technologies for sick broilers using sensors and machine vision have been growing in the past 10 years, and implementations are starting worldwide (Aydin, 2017; Zhuang et al., 2018; Okinda et al., 2019).

Training in data analytics for the poultry industry professionals will become more important to optimize broiler health. It is important to notice that the rankings of key broiler disease challenges were done with educated opinions because diagnostic data were never properly recorded, stored, consolidated, or analyzed in any country to become information available for decision-makers.

One important source of information about broiler health is the information given to the processing plant (Manning et al., 2007b). The final bird counts culled broilers, and dead-on-arrival are obtained (Jacobs et al., 2017). This information can be associated with health risk factors and welfare indicators. Data from the processing plant can include reports of septicemia, skin lesions, cellulitis, ascites, edema, emaciation, bruising, pericarditis, pericarditis, air sacculitis (USAHA, 2021; Coldebella et al., 2018). The information about the average rate of condemnations observed in the past 5 years in the United States and Brazil is presented in Table 7.

Additionally, processing plants collect data on carcass and meat yields and paw quality. All these are markers of health status. This information could be linked to identifying specific pathogens and antibody titers from blood samples frequently obtained before processing. These data need to be used regularly, and alert systems were created to investigate specific cases that indicate health

Table 7 Plant condemnations of broilers in the United States and Brazil from 2016 to 2020

	2016	2017	2018	2019	2020
Plant condemnations			-------------------- % --------------------		
The United States[a]					
Wooden breast, farm + parts condemns	0.53	0.49	0.42	0.35	0.31
Septox condemns	0.14	0.13	0.13	0.11	0.09
Airsac condemns	0.10	0.09	0.07	0.05	0.04
IP condemns	0.02	0.02	0.01	0.01	0.01
Leukosis condemns	0.00	0.00	0.00	0.00	0.00
Brazil[b]					
Myopathies	0.07	0.06	0.09	0.10	0.01
Septox condemns	0.00	0.00	0.00	0.00	0.03
Cellulitis	0.13	0.13	0.13	0.14	0.11
Colibacillosis	0.12	0.14	0.10	0.12	0.01
Air sacculitis	0.05	0.05	0.05	0.05	0.08

Source: [a] USAHA (2021).
[b] Dr. José Mauricio França based on data from Ministério da Agricultura e Instituto Brasileiro de Geografia e Estatística IBGE and Coldebella et al. (2018). The Brazilian system does not consider leukosis condemns.

risks for a future flock in a house or farm or the flocks in the area (Huneau-Salaün et al., 2015).

3.2 Coccidiosis

Coccidiosis ranked high as one of the key disease challenges among the top broiler-producing countries presented herein and in other reports (Jones et al., 2019; Blake et al., 2020; McDougald et al., 2020). This disease has a substantial economic impact. Blake et al. (2020) updated Williams' (1999) compartmentalized model to estimate coccidiosis cost in chickens. These authors estimated a global annual cost of £10.36 billion (US$14.05 billion) at prices of 2016, equivalent to £0.16 or $0.22 per chicken produced. Williams (1999) had calculated over US$3 billion annually, but the broiler population has doubled, and production systems have evolved in a direction that facilitates the infection with this parasite or increases its harmful effects, and the currency values have also changed. In addition, the withdrawal of growth-promoting antibiotics has increased the costs related to coccidiosis (Smith, 2019).

Eimerias may cause disruptions in the gut mucosa and epithelium that exacerbate the dysbacteriosis, malabsorption, and enteritis observed in antibiotic-free broiler production (Fatoba and Adeleke, 2018; Gautier, 2019; Smith, 2019; Fancher et al., 2020; Gazoni et al., 2020; McDougald et al., 2020). In many countries, reused litter became more common in the past 20 years, and oocysts may persist more flock after flock (Barbour et al., 2015; Gazoni et al., 2021). The current models used to calculate costs do not include the additional charges of dysbiosis that increase NE occurrence, the impacts on wet litter, and the consequential issues on pododermatitis, culling, condemnations, and downgrades (Blake et al., 2020; Williams, 1999; Gazoni et al., 2020).

Existing control methods rely on chemical and ionophore coccidiostats, live non-attenuated and attenuated anticoccidial vaccines, and in some countries, phytobiotic products are becoming popular (Williams, 2005; Barbour et al., 2015; Abebe and Gugsa, 2018; Fatoba and Adeleke, 2018; Soutter et al., 2020). Phenylarsonic acid compounds, primarily roxarsone (3-nitro-4-hydroxyphenylarsonic acid) and *p*-arsanilic acid (4-aminobenzenearsonic acid), have been prohibited or withdrawn from the market worldwide by most manufacturers. However, their use in some countries is still allowed. China became the latest country to ban them in May 2019 (Hu et al., 2019).

Ionophores, which are natural metabolites of fungi species such as monensin, lasalocid, salinomycin, narasin, or maduramicin, are common worldwide. Some *Eimeria* strains have gained resistance, but appropriate shuttle or rotation programs still allow the successful application of these products for most broiler producers (Fatoba and Adeleke, 2018; Abebe and Gugsa, 2018; McDougald et al., 2020). However, there are regulatory constraints to use ionophores. In the EU, ionophores were reclassified as feed additives, and they are still in use despite the ban of antibiotic growth promotants. In contrast, the US FDA and Canadian regulators classify coccidiostats as antibiotics and cannot be used in the labeled antibiotic-free production (Smith, 2019).

Chemical products, in contrast, do not have known antibacterial activity and are not used in human medicine. Consequently, they are ideal for broiler antibiotic-free production. Unlike ionophores, each product has a unique way of action. This group includes nicarbazin, zoalene, decoquinate, clopidol, robenidine, and diclazuril (Abebe and Gugsa, 2018; Kadykalo et al., 2018). They are generally safe and have a zero-day withdrawal period in America, except for Robenz with 6 days. But, coccidia develops resistance against these chemical coccidiostats. The exception to some of the last affirmations is nicarbazin. A higher dose than recommended can cause broiler mortality under elevated environmental temperatures (Da Costa et al., 2017). However, there are no reports of resistance against nicarbazin in broilers. Despite the issues previously discussed, anticoccidial use remains a valuable tool for coccidiosis control worldwide (Kadykalo et al., 2018; McDougald et al., 2020).

The new economic model from Blake et al. (2020) included the cost of anticoccidial vaccines that have become the dominant strategy of anticoccidial prophylaxis in layers and breeding stock worldwide. Anticoccidial vaccines are not commonly applied to broilers in all countries (Barbour et al., 2015; McDougald et al., 2020). In the United States, more than 50% of broiler-producing companies have adopted the application of anticoccidial vaccines. Live vaccines have been applied in at least one flock per year, and more than 40% of the chickens produced in the United States have received anticoccidial live non-attenuated vaccines during the past decade (Blake et al., 2020). The bioshuttle programs with a live vaccine applied in the hatchery, followed by an anticoccidial drug, are popular in the United States and many Latin-American countries to reduce drug-resistant *Eimeria* populations (Dalloul and Lillehoj, 2006; Chapman and Jeffers, 2014; Kimminau and Duong, 2019).

The production of traditional live anticoccidial vaccines is limited by their low reproductive index and high production costs, among other factors. Recombinant, subunit, or DNA-based vaccines overcome these limitations by eliciting undesired contaminants and preventing the reversal of toxoids back to their original toxigenic form (Venkatas and Adeleke, 2019; McDougald et al., 2020). Recombinant vaccines are produced using defined *Eimeria* antigens that include specific genes that encode immunogenic protective proteins and harmless adjuvants. Vectors are ligated to these genes to ensure their penetration inside the chicken cells, resulting in efficient translation of the protective antigenic proteins. The search for identifying potent novel *Eimeria* antigens that stimulate both cell-mediated and humoral immune responses in chickens is under development (Dalloul and Lillehoj, 2006; Barbour et al., 2015).

Additionally, improving the efficacy of mass delivery methods of live vaccines and the future DNA-based vaccines is another factor to optimize coccidia control (Williams, 2005; Venkatas and Adeleke, 2019). Nutrient levels of protein and specific amino acids (Keerqin et al., 2017; Gautier, 2019) like glutamine, threonine, and arginine, nutrient digestibility, and feed additives like essential oil blends (Oviedo-Rondón et al., 2006; Muthamilselvan et al., 2016) and probiotics (Miranda et al., 2016) should be revised to achieve optimal immunological responses to vaccines and modulate microbiota to avoid dysbiosis issues (Bryan et al., 2020).

Genetic selection against *Eimeria* has been unsuccessful so far (Smith et al., 2002). However, there is a substantial variance for weight gain or interleukin-10 induction in chickens infected with *Eimeria tenella* (Boulton et al., 2018a) or *E. maxima* (Boulton et al., 2018b). Still, breeding for increased weight gain under challenge alone would not distinguish between resilience/resistance and tolerance (Boulton et al., 2018a,b). The detection of appropriate biomarkers for enhanced immunological responses is under development.

3.3 Necrotic enteritis

According to veterinarians' reports and other studies, NE is the second key disease challenge for broilers (Jones et al., 2019; Boulianne et al., 2020). Due to this disease, the worldwide economic losses are now estimated to be over US$6 billion per year, calculating with the prices of 2015 (Wade and Keyburn, 2015). Furthermore, its impact may be growing as antibiotic-free production systems become more popular (Dahiy et al., 2006; Smith, 2019; Fancher et al., 2020). However, the main difficulty in controlling this disease has been the subclinical presentation before signs are observed. Consequently, treatment is not effective (Timbermont et al., 2011; Boulianne et al., 2020).

NE can be minimized by improving feed quality assurance programs, water quality, digestibility, reducing digesta viscosity with enzymes, house environmental control, and cocci control (M'Sadeq et al., 2015; Boulianne et al., 2020). New strategies include the immunization of breeders (Keyburn et al., 2013). Additionally, it has been proposed to conduct genetic selection to enhance immunity and resistance to NE. There are some candidate genes for this selection. The substantial genetic variations among different chicken strains indicate that it is possible to develop broiler lines with genetic resistance against NE (Zahoor et al., 2018). A better understanding of the netB gene encoding for the pore-forming toxin in *Clostridium perfringens* has been important to understand this disease's pathogenesis. The gene is present in many isolates of *C. perfringens* in healthy or sick broilers (Rood et al., 2016).

The expression of the netB gene in *C. perfringens* is necessary for the development of the disease, and it occurs when broilers are immunologically stressed by *Eimeria* infection (Timbermont et al., 2011; Yang et al., 2019; Dierick et al., 2021), digesta with high viscosity due to the presence of non-starch polysaccharides, undigested material, and ingredients that enhance mucus production (M'Sadeq et al., 2015). Studies have been centered on ingredients such as wheat, barley, meat and bone meal, and fish meal (Zanu et al., 2020). However, broilers fed corn–soybean diets without animal byproducts in the United States or Brazil also present this disease.

Diets with excessively high protein content (40% CP) containing three times more glycine than commercial diets have been proven to increase *C. perfringens* overgrowth (Wilkie et al., 2005). There is some influence of high-protein levels in intestinal health, but diets with protein content higher than 25% are seldom observed under commercial conditions in the starter phases. However, protein digestibility during the first 10 days of life in poultry species is low and can be further reduced by alkaline water (pH > 8). Non-digested protein could play a similar role in increasing *Clostridium* populations and many other pathobiont microbiota of broiler's ceca (Keerqin et al., 2017; Chen and Vitetta, 2020; Zanu et al., 2020). Excessive calcium levels, small particle size (dgw < 75 μm), and high solubility of some sources could increase digesta pH, chelation of Ca by phytic acid, decreasing phytase efficacy, and nutrient digestibility. Excessive nutrients in the hindgut may trigger an overgrowth of enteric pathogens, including *Clostridium*, changes in the microflora and mucosa that facilitate *Eimeria* infection. They could cause the onset of NE incidence (Zanu et al., 2020). Feed additives like tannins and essential oil blends have been tested extensively to control *C. perfringens*, coccidian, and modulate microflora leading to the lesser impact of NE in broilers (Muthamilselvan et al., 2016; Diaz-Carrasco et al., 2016).

The environmental factors previously discussed are also essential to control NE. For example, heat stress, high relative humidity, and high stocking density have been proven to increase NE incidence (M'Sadeq et al., 2015; Tsiouris, 2016; Dunlop et al., 2016; Boulianne et al., 2020). However, reducing stocking density from 0.23 m^2 to 0.27 m^2 per bird had minimal effects in reducing production issues in broilers raised without antibiotics (McKeith et al., 2020). Accordingly, litter management is also important to minimize NE (Hermans and Morgan, 2007).

3.4 Chick quality and early mortality

Chicken early mortality is a major concern for the broiler industry. The main cause is contamination with bacteria and occasionally fungi (Swelum et al., 2021). Embryo or chick contamination not only increases total mortality, but also serves as a marker of other health, performance, and food safety issues that the flock may present later on (Yassin et al., 2009; Yerpes et al., 2020). Chick quality and livability can be influenced by breeder management, nutrition, and health (de Jong and van Riel, 2020). The hen gut microbiome could be transmitted vertically to the progeny (Shterzer et al., 2020) or throughout the eggshell (Maki et al., 2020). Improving broiler breeder nutrition and health has a tremendous impact on broiler health and productivity. The feeding strategies and nutrient levels in breeder nutrition can influence livability, immunity, and progeny performance (Leandro et al., 2011a,b; Oviedo-Rondón et al., 2013; Chang et al., 2016). de Jong and van Riel (2020) connected records from 2174 broiler flocks at the house level in 74 farms with 88 broiler breeder farms and 209 breeder flocks in the Netherlands. The authors observed that breeder flock effects affected carcass condemnations.

Eggshell integrity is essential to avoid contamination. Eggs with hairline cracks usually incubated can reduce hatchability, increase contamination likelihood, and cause more significant mortality (Barnett et al., 2004). In addition, proper egg disinfection with various products (Tebrün et al., 2020) may fail in eggs with hairline cracks. Identifying and minimizing factors that cause eggshell hairline cracks may help to reduce this issue.

Grochowska et al. (2019) conducted a field study seeking to determine factors that affect chick mortality. These authors concluded that breeder flock age, egg storage time, hatcher, and setter type affected chick mortality in the first 7 days of life. Incubation conditions have been related to chick quality and first-week mortality in several studies (Tona et al., 2004; Yassin et al., 2009; Oviedo-Rondón, 2019). Egg storage increases embryo mortality and has several deleterious effects in embryo development, reduces chick quality, the abundance of $CD3^+$, $CD4^-$, $CD8^-$ T cells in chicks, and the humoral response to booster Newcastle disease virus immunization of the birds (Goliomytis et al., 2015). Incubation conditions such as elevated temperatures or suboptimal conditions in the last phase of incubation, especially in the hatchers, also affect embryonic development, immunity, and health post-hatch (Oznurlu et al., 2010; Simon, 2016; Wijnen et al., 2020).

Finally, chick reception and brooding conditions are critical for chick survival. Yerpes et al. (2020) identified the risk factors associated with first-week mortality in chickens using data from one hatchery in Spain. Factors were classified either as internal or individual-dependent and external that included management or environmental factors. Breeder age, chick gender, and breed were the internal factors significantly related to chick mortality. Among the 21 external factors considered, the type of broiler house, the presence or absence of drip cup, egg storage, study year, and season were related to chick mortality. These authors concluded that the identified housing factors and management routines should reduce the first-week mortality rate. de Jong and van Riel

(2020) determined that broiler health variation was mainly explained by broiler farm and day-old chick batch.

3.5 Infectious bronchitis

IBV is one of the main challenges for broiler health worldwide (Jackwood, 2012; Colvero et al., 2015; Jackwood and de Wit, 2020; Legnardi et al., 2020). The avian coronavirus causes the IBV, and depending on the tissue tropism of each strain, its infection can cause acute upper respiratory tract disease or nephritis in broilers (Bande et al., 2017). The most classic IBV includes the Massachusetts serotype, which infects the respiratory tract and is observed worldwide. Nephropathogenic strains are observed more in Asia and Middle Eastern countries. But, specific IBV strains affect other tissues like the gastrointestinal tract (Moroccan IBV-G), proventriculus (QX in China). In addition, the QX IBV present in Asia, Europe, the Middle East, and Africa can affect kidneys and reproductive tract, causing false layers and high mortality (Bande et al., 2017).

Transmission occurs by inhalation or contact with contaminated objects. Morbidity is usually 100%, but mortality varies depending on host factors, strains, and secondary infections (Bande et al., 2017). The current control of this disease includes strict biosecurity and the application of attenuated live vaccines for broilers and live and killed vaccines for broiler breeders (Legnardi et al., 2020). However, the worldwide spread of many antigenic types and emerging new varieties of this IBV make it very difficult to obtain vaccines to protect and prevent transmission (Jackwood and de Wit, 2020).

There are two schools of thought for IBV vaccination that have often opposed each other. Some are in favor of homologous vaccination, others of heterologous one (Legnardi et al., 2020). This dichotomy is based on the principle that a homologous vaccine to the field strain is more likely to generate neutralizing immunity against it. In contrast, heterologous vaccination usually seeks a broader but less specific immunity toward different and potentially unknown circulating strains, in line with the 'protectotype' concept. Nevertheless, 'hybrid' solutions are often applied, including one heterologous strain Mass-based vaccine and one homologous vaccine strain. Several vaccine combinations have been tested so far in line with the different epidemiological scenarios, with particular attention to Mass-like (GI-1) and 793B-like (GI-13) strains, American strains such as Ark (GI-9), Conn (GI-1), DE072, and GA98 (GIV-1), QX (GI-19), Q1 (GI-16), and Var2 (GI-23), suggesting a variable degree of protection depending on the challenge virus. However, based on Mass-like and 793B-like strains, the most common combinations usually ensure good protection against new variants (Legnardi et al., 2020).

Several studies have shown that live IBV, ND, ILT, and avian metapneumovirus vaccines might interfere with each other's replication, humoral response, and induced level of protection when administered together or in relatively short intervals of each other (Jackwood and de Wit, 2020). However, mixing two viruses in a vaccine is the standard practice in the broiler industry, and to improve the efficacy of IBV vaccination, this practice may need to change. Improving the mass vaccine application methods for broilers is another priority in the years to come (Colvero et al., 2015). Failures in immunization can lead to an increased susceptibility to secondary infections and reversion of the vaccine virus to virulence by mutations leading to amino acid substitutions in proteins key for immunogenicity like the S1 glycoprotein (Saraiva et al., 2018). At this moment, all commercially available vaccines cannot be applied *in ovo*. The development of new vaccines may take time. Consequently, the effective prevention method is based on biosecurity with sanitation of all equipment, early and proper vaccination, control of other diseases like mycoplasma and *E. coli* infections, and adequate management of the house environment temperatures, relative humidity, and good air quality (Van Limbergen et al., 2018).

3.6 **Escherichia coli *infection***

Bacterial infections have become more common in many countries, especially those with *E. coli* in countries that adopted antibiotic-free production (Smith, 2019; Fancher et al., 2020; Swelum et al., 2021). Omphalitis, respiratory tract infection, and septicemia are the most common diseases caused by *E. coli* that frequently cause mortality. Pericarditis, airsacculitis, and perihepatitis are observed in subacute forms that often lead to culling or condemnations at the processing plant. Most isolates are from O1, O2, and O75 serogroups (Nolan et al., 2020). There are intestinal and extraintestinal pathogenic *E. coli*. Among the intestinal isolates, there are enteropathogenic, enterotoxigenic, enteroinvasive, enterohemorrhagic, and enteroaggregative *E. coli*. Three extraintestinal isolates include the avian pathogenic *E. coli* (APEC), causing neonatal meningitis, and the uropathogenic *E. coli* (Nolan et al., 2020).

Drug resistance, in many cases, is a big issue. The average resistance rates in *E. coli* to diverse antibiotic classes are higher than 40% in all countries, except for ampicillin in the United States. The resistance rates to fluoroquinolones and quinolones in the United States, where fluoroquinolones are not registered for use, are below 5%. The average of resistant *E. coli* is above 40% in Brazil, China, and the EU, where fluoroquinolones are legalized. However, the banning of fluoroquinolones and quinolones has not eliminated the occurrence of resistant populations (Roth et al., 2019).

The alternative strategies to antibiotics of *E. coli* control include probiotics, prebiotics, synbiotics, and postbiotics. Plant extracts containing essential oil blends, phenols, alkaloids, and lectins have shown some immunomodulatory and antimicrobial activity. However, most of them have variable efficacy (Nolan et al., 2020). Postbiotics were recently introduced in the broiler industry. These products are the soluble factors, products, or metabolic byproducts, secreted by live bacteria or released after bacterial lysis, such as enzymes, peptides, teichoic acids, peptidoglycan-derived muropeptides, polysaccharides, cell surface proteins, and organic acids. The potential beneficial effects as anti-inflammatory, immunomodulatory, antihypertensive, antiproliferative, hepatoprotective, and antioxidant agents are still under evaluation (Swelum et al., 2021).

There are three commercially available vaccines against colibacillosis in the market worldwide: Nobilis *E. coli* (MSD Animal Health, Summit, NJ), Poulvac *E. coli* (Zoetis, Florham Park, NJ), and Nisseiken Avian Colibacillosis Vaccine CBL (Nisseiken Co., Ltd., Tokyo, Japan). Nobilis is an inactivated subunit vaccine consisting of fimbrial antigen F11 and a flagellar toxin. Poulvac is a live attenuated *E. coli* EC34195 serotype O78 with deleted aroA gene as the active substance. The immune response is mainly cell-mediated by CD 4+TCRVβ1+ on the mucosal surfaces producing immunoglobulin A (IgA) and CD8 cells. The Nisseiken is a live mutant vaccine that contains 107–109 colony-forming units/dose of AESN1331 O78 APEC strain, which has a deleted crp gene (Swelum et al., 2021).

Recent reports indicate that a recombinant or subunit multiantigen vaccine comprising a combination of common surface proteins can produce significant levels of IgA and IgY against specific antigens and impose immune responses favorable for killing the bacteria. The recombinant vaccine has reduced bacterial growth of multiple APEC serotypes, reduced bacterial load in organs, and reduced air sac lesions (Ebrahimi-Nik et al., 2018). However, mass evaluations need to be conducted. Vaccination against *E. coli* still faces several challenges, like inducing cross-protection against various APEC serogroups and massive delivery methods. Generally, studies revealed that the inactivated vaccines protected homologous challenges only (Swelum et al., 2021).

Other alternative control strategies include biosecurity, proper water sanitation, and good air quality (Nolan et al., 2020). In addition, the application of bacteriophages has been demonstrated to be successful against several APEC (Żbikowska et al., 2020). Finally, the use of toll-like receptor ligands and agonists has been evaluated to activate signaling cascades leading to the expression of various innate immune responses. These include cell wall components such as lipopolysaccharide, peptidoglycans, bacterial deoxyribonucleic acid, and double-stranded viral ribonucleic acid. However, the synthetic agonist products like CpG-oligodeoxynucleotides and polynosinic:polycytidylic acid can be easier to produce and apply (Swelum et al., 2021).

4 Conclusion

The economic impact of all broiler infectious diseases indicates a strong need to develop more work in this area. The optimization of broiler health comes with a better understanding and monitoring of the whole production system in each location. The data presented in this chapter indicate that intestinal and respiratory diseases are the main aspects to improve worldwide. There are big challenges to improving immunity against coccidiosis, *Clostridium* spp., IBV, and *E. coli*. These four pathogens cause major infectious diseases for broilers. Proper incubation and broiler-house environmental management play an important role in preventing and controlling diseases caused by these and other pathogens. Improving chick quality and reducing early mortality is a priority to enhance broiler health. Feed and water quality are necessary to control all main pathogens except for IBV. Feed composition and additives may help modulate the microflora that influence the pathogenicity or virulence of the three intestinal pathogens. Broiler breeder management, nutrition, and immunization play a big role in controlling these and other diseases. Genetic selection to develop more host resistance against *Eimeria* and *Clostridium* species is possible, but it may take a long time to achieve. Genetic resistance against *E. coli* is very difficult since this is one of the most common commensal species. Enhanced immunity and genetic resistance against IBV are problematic due to the high genetic variability of this virus. Diagnostic methods should include more information from each live production phase, including hatchery, transportation, farms, and processing plant. Data from serology and PCR-DNA-based techniques are needed for better pathogen identification and surveillance of present diseases and emerging ones. The whole toolbox of data analytics should be applied more frequently to optimize broiler health.

5 Where to look for further information

Readers interested in learning more about the current status of broiler or other poultry infectious diseases should visit the United States Animal Health (USAHA) website and obtain their annual reports and other publications. There is one yearly report on transmissible diseases of poultry and avian species from the Committee on poultry and other avian species. https://www.usaha.org/transmissible-diseases-of-poultry-avian-species.

Another thorough material to learn about all infectious diseases of broilers is the book *Diseases of Poultry* (eds D. E. Swayne, M. Boulianne, C. M. Logue, L. R. McDougald, V. Nair, D. L. Suarez, S. Wit, T. Grimes, D. Johnson, M. Kromm, T. Y. Prajitno, I. Rubinoff and G. Zavala). The extensive lists of references will provide further information to readers.

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