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A Review on Significance of Public Health Issues Related to Poultry Campylobacteriosis

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A B S T R A C T

The goal of poultry industry worldwide is the production of safe food products, via efficient and goal-oriented health care to prevent the development of disease conditions in poultry. However, a several number of poultry diseases can negatively affect the breeding values and have the potential to be zoonotic and transmit the infections to humans such as Campylobacteriosis. *C. jejuni* is highly prevalent in commercial poultry farms and act as major reservoirs of the infection. Horizontal transmission from the environment is considered to be the primary source of bacterial foodborne worldwide. The high prevalence of *Campylobacter* spp. in poultry meat is a result of several contamination and cross-contamination sources in the entire production chain. Recent investigations demonstrated that various stages of food processing in slaughterhouse and consumption of raw or undercooked poultry meat is considered the significant risk factor for human Campylobacteriosis worldwide. Furthermore, survival factors such as biofilm formation and antimicrobial resistance, enable its persistence during food processing. On the other hand, the increase of multiple and multidrug-resistant *Campylobacter* worldwide is not only related to the over-consumption of antibiotics in human medicine, but also in poultry production chain as growth promotors and/or to treat and prevent bacterial infections. Antibiotic resistant *Campylobacter* presents an obvious and impending challenge to One Health. In the future, the consumer expectations for high standards quality of poultry products will strongly influence the production methods. This means that farmers, stockholders', veterinarians, and all other partners involved in the production chain, will have to share more responsibilities and the cooperation should be intensified. This review represents an updated overview of the global epidemiology, the correlation of official control, the disease associated with food handler and the importance of food safety with respect to Campylobacteriosis.

Keywords: *Antimicrobial resistance, C. jejuni*, Campylobacteriosis, *Food safety, Human, Poultry*

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1 Introduction

Campylobacter comprises Gram-negative species with non-spore-forming a spirally curved shape and colonizes in the intestinal tracts, oral cavities, or urogenital tracts of most warm-blooded animals (1). *Campylobacter* can transform into filamentous or coccoid to adapt to the environmental stresses. This survival mechanism is sometimes recognized in the literature as viable, but non-culturable cells, making precise detection and enumeration of *Campylobacter* species in food and/or environmental samples more difficult (1-3). Moreover, during this stage, the pathogen preserves its metabolic activity, which could increase the bacterial virulence. Most of the *Campylobacter* species are mobile caused by a polar flagellum present on one or both ends of the cell (4, 5). The species can grow at pH between 6.5 and 7.5 and the temperature between 37˚C and 42˚C. Hence, they are considered thermophile and birds have been largely considered as natural hosts of these organisms. According to the described properties of this organism, a typical stool culture at 42˚C on media containing cephalothin for the recovery of *C.* jejuni and *C.* coli from cases of human diarrhoea may not be suitable for the growth of other species, such as *C.* fetus or *C.* upsaliensis, which, intermittently, induce human infection (6, 7). Besides diarrhoea, other gastrointestinal infections associated with different *Campylobacter* species are shown in Table 1. *Campylobacter* spp. are fastidious bacteria, sensitive to drying, heat, freezing, UV, disinfectants and extremes of pH, high/low temperatures and with particular growth requirements (8, 9). Survival is accomplished by lower temperatures (4–10°C), darkness and a moist atmosphere. Hence, retail storage conditions for poultry meat ins several countries are frequently ideal for survival of the *Campylobacter*, as long as meat is not frozen (10, 11). Although the bacteria are considered to be sensitive to stress related to environmental conditions, in the course of evolution, they were able to develop several complex mechanisms of survival and virulence factors, including motility, chemotaxis, adherence, and invasion of the host cell, structures of the cell envelope, iron uptake system, multidrug and bile resistance toxin production, and mechanisms of responses to stress (12, 13). In addition to several virulence factors, showed that *Campylobacter* spp. isolated from poultry meat are resistance to several antibiotics. Meanwhile, it has not been possible to prevent the spread and control *Campylobacter* at farm level since they are mostly resistant to different antibiotics. Thus, it has not been able to rearing *Campylobacter* free poultry to the consumer (14, 15). Transport, handling and experimental analysis of samples for *Campylobacter* are cumbersome and conventional techniques applied for many other bacteria are generally not suitable. Molecular methods for detection and characterization of *Campylobacter* spp. have proved prosperous and should be further explored to develop rapid and standardized assays for detection and quantification of *Campylobacter* in samples from humans, animals and food (16, 17).

Table 1. *Campylobacter* species related to the human gastroenteritis (18)

Campylobacter Species	Gastrointestinal Infections
C. coli	Gastroenteritis and acute cholecystitis
C. concisus	Gastroenteritis and Barret esophagitis
C. curvus	Liver abscess, Barrett esophagitis and gastroenteritis
C. fetus	Gastroenteritis
C. helveticus	Diarrhoea
C. hominis	Ulcerative colitis and Crohn's disease
C. hyointestinalis	Diarrhea and gastroenteritis
C. jejuni	Acute cholecystitis and celiac disease
C. insulaenigrae	Abdominal pain, diarrhea and gastroenteritis
C. lari	Gastroenteritis and septicaemia
C. mucosalis	Gastroenteritis
C. rectus	Ulcerative colitis, gastroenteritis and Crohn's disease
C. showae	Ulcerative colitis and Crohn's disease
C. sputorum	Gastroenteritis
C. upsaliensis	Gastroenteritis
C. ureolyticus	Gastroenteritis, Crohn's disease and ulcerative colitis

2 Prevalence of *Campylobacter* in Poultry

Campylobacteriosis has been reported in both domestic and wild birds, especially commercial poultry, due to a higher stocking density in poultry farms (8, 19). Poultry has been considered as the main source of food-related transmission of *Campylobacter* species to humans (20, 21). *C. jejuni* is a prevalent commensal microorganism in chicken. Poultry is also a reservoir of other *Campylobacter* species including *C. lari*, *C. upsaliensis*, and *C. concisus* (6, 22, 23). This bacterium generally transmits horizontally to flocks. It was reported that *Campylobacter* species are usually abundant in the surrounding environment of poultry farms, such as soil, water sources, dust, surfaces and air (4, 14, 21, 24, 25). Various factors in commercial poultry farms may impact on the outbreak of Campylobacteriosis, including the type of breeding, housing system, region, and biosecurity standards. It has also been reported that the prevalence of Campylobacteriosis is high in months, in which the temperature is high, leading to a higher population of flies (25, 26). In most countries, the rate of infection is higher than 50% in broiler, layer, and turkey flocks (27, 28). *C. jejuni* is the predominant species in poultry, while *C. coli* is less common and *C. lari* is rare (6, 11, 25, 29). Flocks younger than 3 weeks of age are rarely affected and there is also a seasonal variation, since infection rates are higher in spring and fall compare to winter and summer (30, 31). In general, there are no evidence has been found either for vertical and/or for horizontal transmission from one flock to the next via persistent house-contamination. The probable sources for horizontal transmission include contaminated water, using old litter, farm workers, contaminated footwear, insects, wild animals especially rodents, farm animals, scavenger birds, feed contaminated with faeces of infected chicks, house flies, visitors, and equipment (6, 21, 24, 25, 32-35). Various sources of *Campylobacter* infection in poultry and also outbreak of human Campylobacteriosis is presented in Figure 1.

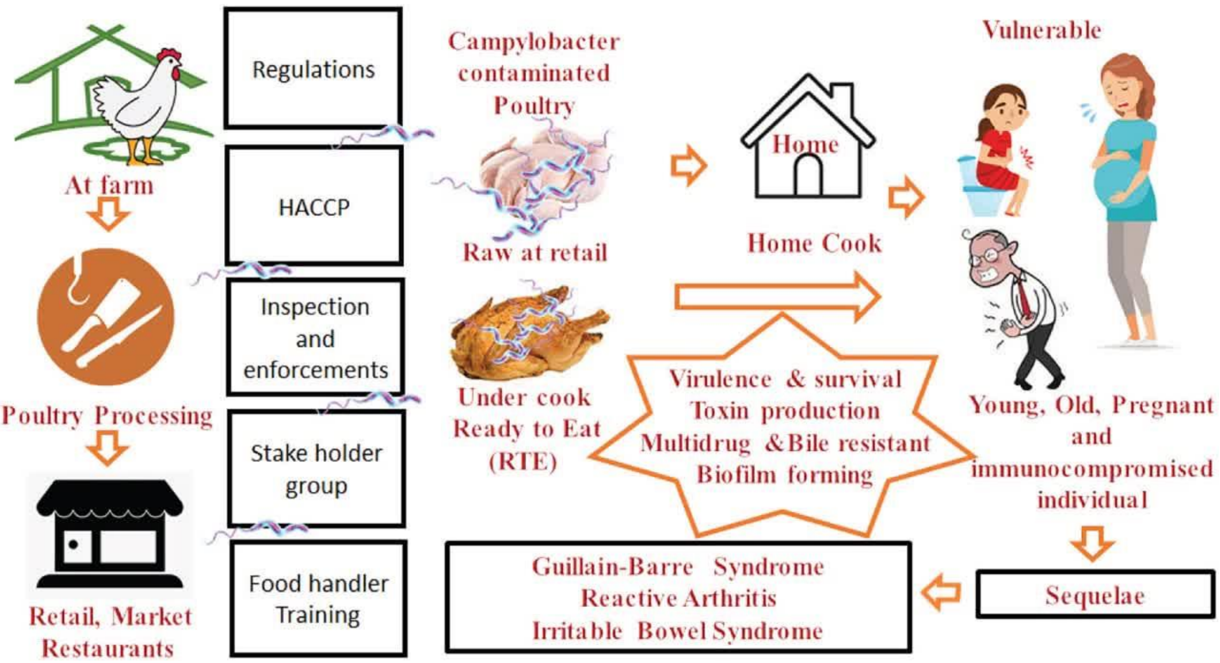

Figure 1. Different sources of *Campylobacter* infection in human (36)

Livestock such as cattle, sheep and pigs are frequent carriers of *Campylobacter* by acquiring bacterial infection from their dams. Poultry, especially chickens, are colonized throughout their gastrointestinal tract; colonization of the caecum can reach 10^9 CFU per gram of caecal contents (21, 37). During 2008, an EU-wide baseline investigation, which included 26 member states, was conducted at broiler slaughterhouses to specify the prevalence of *Campylobacter* in broiler carcasses. The result showed that *Campylobacter* colonized broiler batches at 71.2% and *Campylobacter* contaminated broiler carcasses at 75.8%, and it was noted that the prevalence in individual member states varied from 2% to 100% and from 4.9% to 100%, for caecal contents and carcasses, respectively (38). Among 26 member states, Ireland had the fourth highest prevalence of *Campylobacter* (83.1%). *Campylobacter* prevalence in broiler 394 batches and 98.3% of carcasses (n=394) being contaminated with *Campylobacter* at the end of the slaughter process (39). In a further study of poultry meat revealed remarkable lower *Campylobacter* concentrations both in caecal content and neck skins, were reported from birds reared on organic farms and the equipment of slaughter houses were cleaned and disinfected between every batch, compared to conventional rearing farms. Low-welfare batches reared with highly stocking density and different ages indicated higher prevalence of Salmonella both in neck skins and caecal content, with a statistically significant difference compared to high-welfare batches in caecal content (40).

Investigations on prevalence of *Campylobacter* spp. in broiler chicken carcasses of slaughterhouse in south of Brazil, the obtained results, showed that there are no significant differences in prevalence in relation to the size of the slaughterhouses. The results reinforce the need to promote in the execution of strategies to prevent and control of *Campylobacter*, in order to protect consumer's health and contribute for the maintenance of Brazil's position in the international poultry meat market (41). Meta-analysis of the prevalence of *Campylobacter* in different animal food products in 2020 indicated that *C. jejuni* is the most prevalent species worldwide and broiler meat is the main contamination source for human. and this suggests public health importance and persistent monitor of national authorities in aspect of poultry meat processing. Spread of Campylobacteriosis in chickens, with the adulteration level of poultry meat products, differs remarkably among countries, justifying discrepancies in the intervention policies needed (42, 43). Democratic supremacy extremely affects dietetic quality or meat ingestion and, therefore, food security which means that rate of outbreak of human Campylobacteriosis is based on the country policies of prevention of zoonotic diseases and also people taste in relation to meat consumption. Also, civil liberties and political are significantly influences the poultry meat consumption. In Finch poultry during the five study years, out of 380 isolates of *C. jejuni*, 114 of the 118 farmhouses dispensing positive chicken batches for *C. jejuni* (96.6%). A quarter of chicken farms transported *C. jejuni*-inhabited batches to slaughter each year (42).

In the broiler production chain, the main phases consist of farm rearing, transport to slaughter houses, following by meat processing, retail markets, and consumers This pathogen can persist along the entire chain with high concentrations at consumer level (44). Colonization of *Campylobacter* in poultry is usually in accordance with horizontal transmission at farm level (4, 6, 37). Meanwhile, the spread of this microorganism among breeding farms could also be facilitated through the utilization of insufficiently cleaned or disinfected transport crates (21, 45, 46). Chicken feathers and intestinal disorders due to stress, can lead to spread of contamination. Within the slaughterhouse, the stages of defeathering, bleeding, evisceration, washing, and chilling are considered as vital phases in the slaughterhouse process as they can result in significant contamination (47, 48). Hygienic management of evisceration is necessary as rupture or leakage of the intestine could increase contamination of carcasses and the processing environment (49, 50). Furthermore, at consumer level, cross-contamination of ready to eat food products in the kitchen, with contaminated meat and consuming undercooked chicken increase the risk of developing Campylobacteriosis, which has been described previously.

3 Food Safety

The disease is initially spread horizontally, and vertical transmission is thought to be completely uncommon. The genus *Campylobacter* is commonly found in nature and can contaminate drinking water and infections by this microorganism in humans are principally transmit by contaminated food (1, 4, 51, 52). In most cases, *C. jejuni* is transmitted via the faecal-oral route, and among sporadic human cases of infection, direct contact with live poultry, pets and other animals, consumption of contaminated and undercooked poultry meat, raw milk or unwashed vegetables and also drinking water from untreated water sources are frequent and important sources of infection (53-55). *Campylobacter* spp. cause more globally human cases of bacterial foodborne disease than other bacterial pathogens and it is the most prevalent reported foodborne disease in the developed world (56, 57). The process of handling and preparation may commonly result in spread of *Campylobacter* from naturally contaminated poultry meat to hands or food contact surfaces in the home kitchen, which are also considered to be a significant threat to consumers (8, 52, 58). Extensive research in aspect of consumer food safety has been performed internationally to specify consumer food safety behaviours and behavioural influences. Clinical signs of *Campylobacter* infection are often indiscernible from those caused by other enteric pathogens such as Salmonella and Shigella. In developing countries, infection is generally restricted to children, indicating that a high level of exposure in early stages of life or repeated exposure resulted in development of protective immunity (9, 59-61). In industrialized countries, experimental approved cases of *Campylobacter* infection peak in distinct age groups, 0–4 years, 20–25 years and ultimately in the 65 years and older age group (62, 63). The incubation period for human Campylobacteriosis is generally 2– 5 days. Most patients have 3–7 days of diarrhoea with different severities, abdominal pain, lethargy, fatigue, decreased appetite, nausea, fever, headache and vomiting (24, 25, 64). *Campylobacter* infections are usually self-limiting within 1 week, but in some patients, the illness may aggravate and last longer, and in small part of the patients, symptoms of *Campylobacter* poisoning may persist for up to 3 weeks (64-66). In developed countries, the duration of the disease is usually more severe compared with developing countries (32). Furthermore, Campylobacteriosis may be in association with complications happening in 1% of cases which include peripheral neuropathies, the Guillain–Barré Syndrome (GBS, neurological disorder identified by weakness of limbs, possible involvement of respiratory muscles, anaemia, and sensory loss); reactive arthritis (REA, involving knees and ankles, occurring about a month after infection and developing for as long as 5 years); and functional intestinal disorders, including irritable bowel syndrome (IBS) (9, 67, 68). *Campylobacter* spp. are responsible for 15% of food-borne disease-related hospitalizations and 6% of food-borne illness related deaths, and an estimated 400 million cases are reported per year (51, 69). The economic losses arising from *Campylobacter* infections are significantly related to treatment costs, loss of productivity for infected people, and also costs for prevention and controlling the pathogen (24, 70). The outbreak of Campylobacteriosis is considerably elevated in the last couple of decades with a high morbidity rate and significant infant mortality (33, 71, 72). Moreover, emerging new species and antibiotic resistance in most common species, including *C.* jejuni are additional challenges in the control of *Campylobacter* infections (35, 73). Since the founding of the China National Center for Food Safety Risk Assessment in 2011, there has been increasing concern about food safety at the governmental level (74). According to the annual food poisoning statistics announced by the Ministry of Health, Labour and Welfare in Japan, *Campylobacter* replaced Salmonella and Vibrio parahaemolyticus as the main bacterium responsible for food poisoning in 2003 (75). The rate of Campylobacteriosis in New Zealand is almost 160 cases per 100,000 people, and this rate is higher than in the rest of the developed world (76). This is 12 times higher, than the rate United States; four times higher than the rate for Canada, Germany, and The Netherlands; and nearly 6 times higher than the rate in Norway (62, 67, 77). In Brazil, research on *Campylobacter* is limited compared to developed and developing countries; however, over the years, investigations in accordance to human Campylobacteriosis conducted in different regions of Brazil have indicated diverse rates of 11% and 98% (78). The epidemiological data from Asia, Africa, and the Middle East indicated that *Campylobacter* infection is prevalent in this region although the data is imperfect. The total number of *Campylobacter* infections in 3702 cases with a culture-confirmed *Campylobacter* infection were 545 in Australia, 1846 in Canada, and 1311 in the United States) and Canada was estimated to be about 145,350 cases per year (79). British Columbia had an annual *Campylobacter* outbreak rate of 37.74 cases per 100,000 people in 2017 (80, 81). In comparison, Japan had a rate of 1,512 cases per 100,000 people and New Zealand had a rate of 161.5 per 100,000 people within the last decade (75, 76, 82, 83). In USA, the surveillance system, new legislations and control strategies led to the reduction of several foodborne pathogens including Salmonella, Listeria, and E. coli O157:H7 from 2006 to 2014, but not *Campylobacter* and Vibrio (31, 65). Figure 2 is a map illustrating records of some reported cases of *Campylobacter* outbreaks in some countries of the world. Overall, both individual cases and infections of Campylobacteriosis are usually widespread. A serious methodological effort is needed for public awareness and disease control with the involvement of all shareholders. At first, a persistent ongoing surveillance plan is required with appropriate laboratory infrastructure for the identification along with basic and efficient gastrointestinal disease control programs, especially in developing countries. Furthermore, a principled approach is required to control *Campylobacter* infections, including suitable monitoring of disease burden, source attribution, risk evaluation and management, surveillance of antimicrobial resistance, and assessment of possible control measures. However, thermophilic *Campylobacter* is ubiquitously present, but most recent outbreaks were frequently associated with water and food cross-contamination with animal shedding. Although, animals are asymptomatic carriers of *Campylobacter*, cross-contamination of the food chain with animal waste at the different stages of slaughtering, processing and marketing, direct human contact with pets, and contamination of drinking water with animal excreta probably resulted in infection outbreaks in human (64, 84, 85). Indeed, *Campylobacter* spp. and sources of food chain contaminations should also be taken into account while developing disease control strategies.

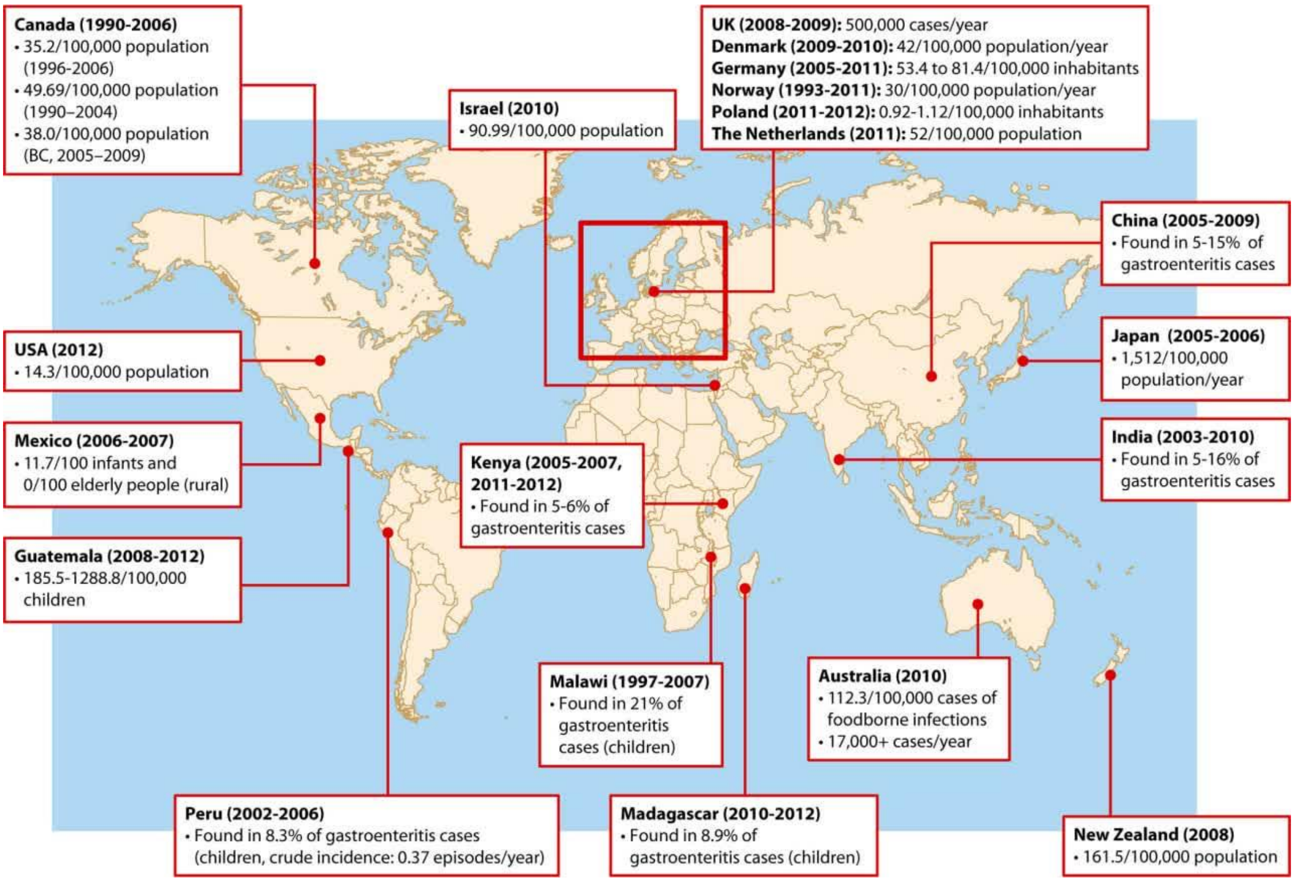

Figure 2. Incidence and prevalence of Campylobacteriosis in some countries (18)

4 Antibiotic resistance and associated problems

The development of antibiotic resistant bacteria, which is common in both, animals and humans, will also be a continuous public health hazard. Currently, only a few authorized pharmaceutical veterinary products will be available for the treatment of poultry and food producing animals (86-88). The development of antibiotic resistance in bacteria, which are common in both animals and humans, is an emerging public health hazard (87, 89, 90). Controlling these foodborne organisms requires a broader understanding of how microbial pathogens enter and move through the food chain, as well as the conditions that promote or inhibit growth for each type of organism. It is generally known, that supplementation of poultry feed with antibiotic growth promoters (AGPs) improves performance of live-stock (91-93). The effect of AGPs on gut flora, results in improvement of digestion, better absorption of nutrients, and a more stable balance in the microbial population. As consequence, the prevalence and severity of intestinal disorders are reduced.

However, AGPs also can increase the prevalence of drug-resistant bacteria (94-97). Based on "Precautionary Principle" and experiences made in some European countries, the EU completely banned the use of antibiotics growth -promoting in feed of food producing animals (27). Field observations in Europe showed that the poultry industry faced several problems after the ban of AGPs. The impact of the ban has been seen on the performances including body weight and feed conversion rate as well as on the rearing husbandry including wet litter and high ammonia level, animal welfare problem (footpad dermatitis) and general health issues including enteric disorders due to dysbacteriosis and clostridial infections. Investigations indicated that competitive exclusion, prebiotics, probiotics, enzymes, and acids can reduce the incidence and severity of clostridial infections in poultry (94, 96-100). The treatment of the domestic animals with antimicrobial drugs to promote the overall health and produce higher-quality products could result in developing resistance of bacteria to these antibiotics and suppressing sensitive bacteria. Therefore, consumption of such contaminated food from animal origin by human may lead to detrimental and undesirable health consequences (9, 51, 101, 102). Lately, investigations had indicted an elevated frequency of antimicrobial-resistant and multidrug resistance *Campylobacter* strains, especially macrolides, fluoroquinolones, and tetracyclines (103-105). Significant press and public attention have pointed to the agricultural industry as the main reason of antibacterial agents' resistance. Although, this is still a controversial conception, with information arising from many studies finally being non-decisive. Several investigations have been conducted to characterize, whether or not this connection is true (31, 84, 88, 89, 94, 102, 105-107). Ultimately, this may be a case of relationship not showing cause and effect. While the increase in resistance in the clinical sector is reflected in the agricultural sector, these may be very independent outbreaks. This means that the cause of antimicrobial resistance increase in human is overuse of antibiotics in poultry rearing and antimicrobial resistance outbreak in poultry but in some cases of human Campylobacteriosis the antimicrobial resistance occurs with no effect and source of poultry. The reasonable use of antimicrobial agents as a whole perhaps finally combats antibiotic resistance (66, 108). Several studies have been performed to specify if there was a relationship between antibiotic resistant *Campylobacter* in poultry with human Campylobacteriosis. In a study, the researchers reported a high antibiotic resistance of *Campylobacter* spp. in Lithuanian- and Latvian-origin broiler chicken meat and Estonian clinical isolates. Similar antibiotic resistance patterns were found for broiler chicken meat and human *Campylobacter* isolates (109). This finding suggests that broiler chicken meat poses a potential threat to humans as it is well known that broiler chicken meat is an important source of human Campylobacteriosis. To minimize the emergence of *Campylobacter* resistance, it is very important to comply common policies and enforcement proper practices on antimicrobial usage at the farm level. In another study, the investigators found the similar *C. jejuni* clonal complex in both isolates from Estonian humans and from Estonian and Lithuanian broiler chicken meat and also the resistance to one or more antimicrobial agents was revealed for 62.5% of the *C. jejuni* isolates, which shows the public health concern (110). This suggests that imported broiler chicken meat is a potential source of *Campylobacter* human infections in Estonia. According to the research about antimicrobial resistance profiles of *Campylobacter* species in humans and animals in Sub-Sahara Africa, the findings provide evidence of thermophilic *Campylobacter* infection in humans and animals and high levels of antimicrobial resistance in Sub-Saharan Africa, emphasizing the demand for strengthening both national and regional multisectoral antimicrobial resistance standard surveillance protocols to curb both the Campylobacteriosis burden and increase of antimicrobial resistance in the region (111). The findings of another study demonstrated a high antimicrobial resistance to quinolones and tetracycline of *C. jejuni* obtained from poultry food chain and patients with diarrhoea, which was closely in accordance with the presence of several virulence genes playing a vital role in the pathogenesis of *Campylobacter* infection (112). *Campylobacter* is an important zoonotic and foodborne pathogen and is increasingly resistant to antibiotics used for human and veterinary medicine (106, 113). Due to its vital role in public health and its rising resistance to antibiotics, especially fluoroquinolones, *Campylobacter* has been identified as one of the critical antibiotic resistant threats of high priority by both WHO and the CDC (107). The increase of multiple and multidrug-resistant *Campylobacter* worldwide is not only related to the overconsumption of antimicrobial drugs in human medicine, but also in animal breeding as growth promotors and/or to treat and prevent bacterial infections (101, 102). Antimicrobial resistant *Campylobacter* poses a great risk especially to human health resulted in treatment failures, longer hospitalization, and increased morbidity and mortality (66). This suggests the high complexity of antimicrobial resistance in the poultry industry, as illustrated in Figure 3.

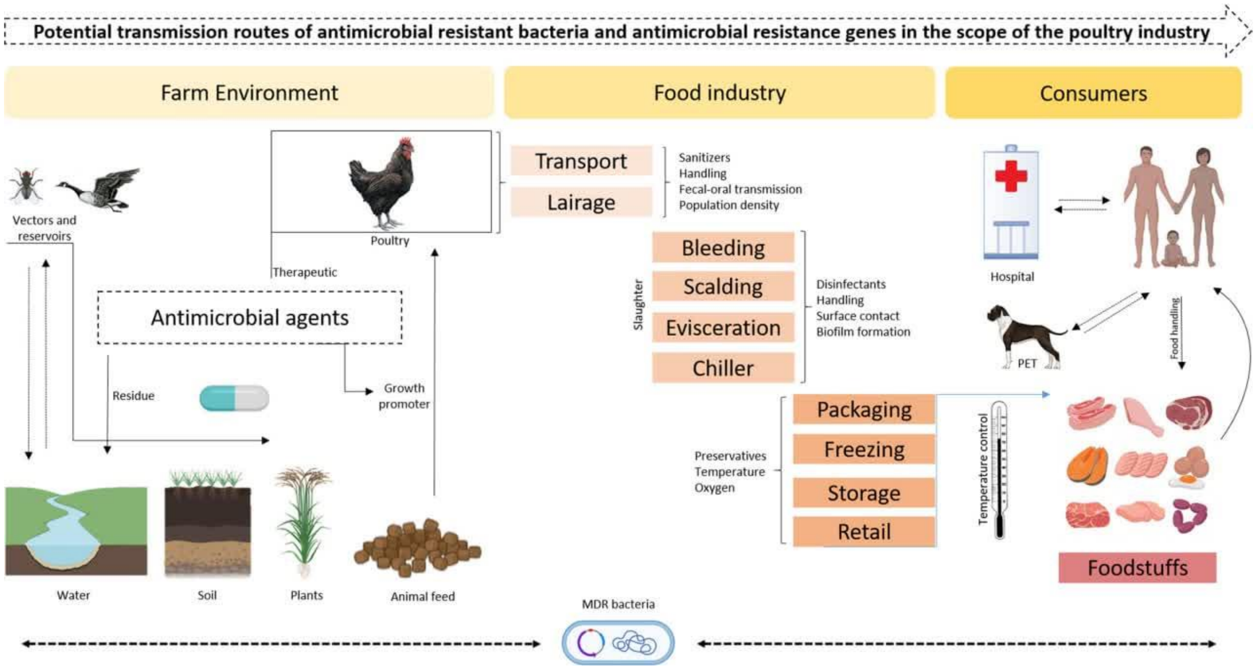

Figure 3. Potential transmission routes of antimicrobial-resistant bacteria in the poultry industry (114)

5 Welfare of Poultry

Investigation related to the poultry welfare and risk of infection, revealed that flock size and age were significant risk factors for *Campylobacter* colonization in broilers. In addition to hygiene practices, animal welfare and health may also play a critical role. Also, there is a link between arthritis in broiler chickens and *Campylobacter* colonization (115-117). Moreover, investigators reported that a welfare scoring system on farms could be useful with *Campylobacter*-positive flocks more likely to be detected on low welfare scoring farms. In conclusion, improving welfare measures may decrease stress in birds lead to a reduced risk of *Campylobacter* colonization. Currently, there is great concern about the welfare of animals, hygiene, and disease control that may result from great genetic pressure to boost egg and meat production. Indeed, genetic pressure to improve the productive performance of animals adversely affects animals' welfare and natural immunity and thus disease tolerance (20, 56, 113). However, genetic selection occurs with improved practices of husbandry, disease control, and nutrition manipulation. The most achievable alterations have been a decrease in the market age of approximately 4 weeks, a better growth rate, improve the feed conversion rate, greater breast meat yield, and a higher laying rate and daily egg mass. However, there is a huge unease, that the serious animal welfare problems and disease have already been initiated due to the above- mentioned selection pressure. Increasing selection pressures also hinder animals' freedom (118).

6 Future expectations

Poultry is the main contributor to human Campylobacteriosis and is still one of the most prevalent infectious diseases, that is a predictable threat to consumers in the years ahead. Numerous investigations demonstrated that complete clearance of poultry production chain from *Campylobacter* is not feasible. Therefore, cross-contamination of *Campylobacter* from poultry to human is still remained as a threat. Accordingly, this suggests that the integrated endeavour from all stakeholders from the aspect of biosecurity at the farm level, Hazard Analysis & Critical Control Point (HACCP) at processing along with distribution and ultimately inform the consumer about the risk associated with it (36, 119). In future improvements in laboratory diagnosis, such as diagnostic micro-array and other technologies, will allow faster, more sensitive and more accurate diagnosis and early detection of infectious diseases, and allowed early intervention, will become a reality. However, only a few authorized pharmaceutical veterinary products will be available for the treatment of poultry as food producing animals. Future scientific findings on the pathogenic mechanisms of bacteria will help to improve the treatment of bacterial infections, and instead of non-specific antibiotic therapy, new drugs will be able to target the signalling mechanisms, which are able to disrupt the pathogenic effects of the pathogen bacteria. Genetic resistance and selective breeding to improve production traits and health is a long-standing goal of the industry. The desire to enhance breeding strategies with the use of molecular techniques (genetic linkage maps) will lead to the characterization of genome structure and genes that are associated with production traits and disease susceptibility and resistance. This will allow selecting bird lines that are genetically resistant to several pathogens. In addition, improvement of rearing technology, management and nutrition will help to maintain bird comfort. Increased feeding cost and raw ingredient prices as well their availability will negatively influence the growth of the industry and consumers' purchasing power, particularly after the COVID-19 pandemic as well as the current situation in Ukraine and Soviet Union. Moreover, increases in biogas and biofuel production will decrease the land available for grain production and feed for animal productions. This phenomenon will hinder the strategic vision of some countries, to achieve their future goals. Specifically, there could be a marked increase in the cost of feeding for animal production and elevated product prices. In the future, the feed industry has an obligation to ensure the quality of feeds and that they are free of pathogens and ecologically friendly. Besides, limited water resources and climatic changes are also expected to adversely affect poultry production costs and strategic planning to meet per capita consumption in some countries. The movement of poultry and poultry products as well as the strong production competition and cost differences from around the world will accelerate the cost and global movement of poultry and its products. This phenomenon will increase the possibility of disease transmission into places thought to be free from poultry diseases.

Vaccination is regard as one of the most beneficial bio-pharmaceutical interventions, due to its ability to induce protection against infectious diseases through targeted activation of the immune system. Many valuable new vaccine production technologies have been developed. The future progressive in vaccine production technologies, such as recombinant, subunit, reverse genetic and nucleic acid vaccines, can significantly reduce the cost of vaccines, ensure the efficacy, and allow easy and rapid intervention to face the steady mutation of the microorganisms. Furthermore, the development of efficient vaccines against bacterial infections will lead to a reduction of the use of antibiotics. However, SARS-CoV-2 is not linked with poultry or its products, it will likely influence the global poultry trade, due to lockdown and restrictions that is applied to control the spread of the virus (120). Globally, poultry diseases will continue to be the primary issue for the poultry industry and its strategic future. The outbreak of any disease can turn into an epidemic and have an extensive adverse influence on the global trade of poultry products. As explained, Figure 4 represents the summary of various methods to lower the risk of human Campylobacteriosis.

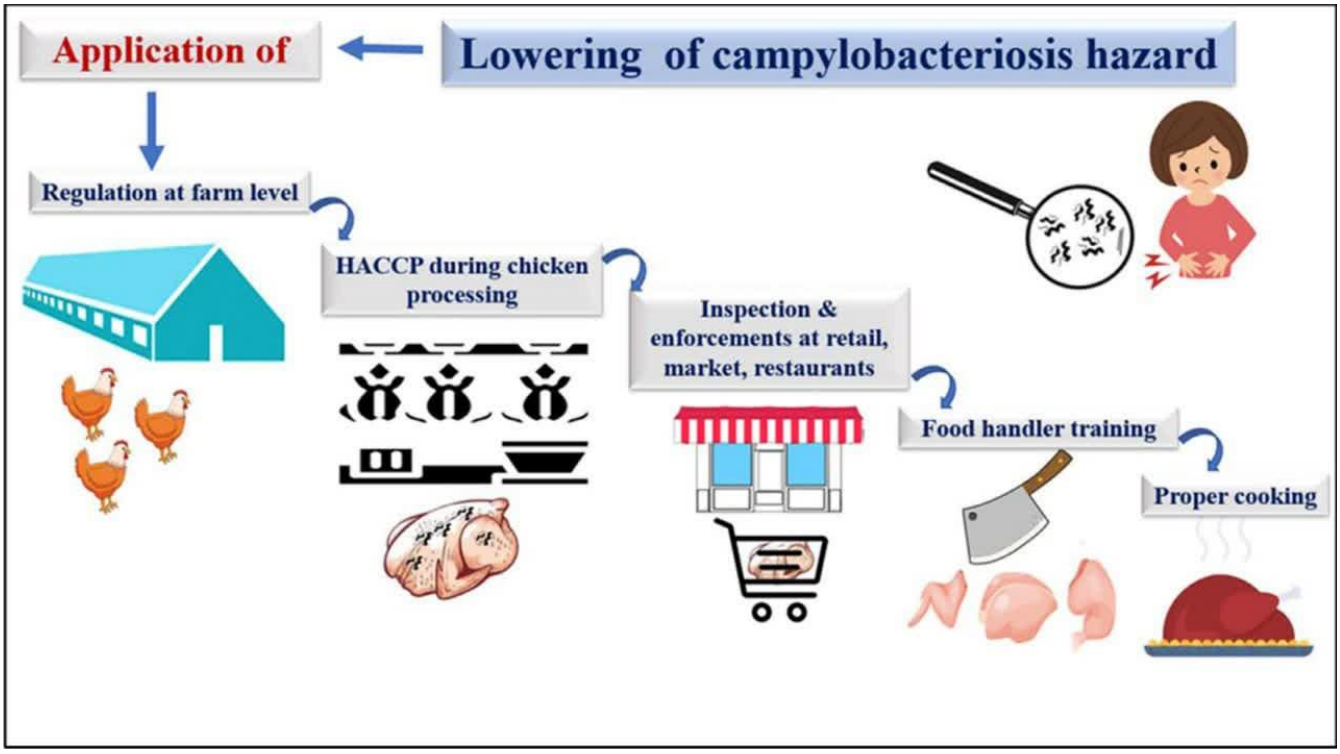

Figure 4. Lowering the risk of poultry Campylobacteriosis by implementing various strategies at different stages (121)

7 Conclusion

In the future, the global cooperation and trade will force the governments to harmonize the existing different legislations related to trade, animal disease control, animal nutrition as well as the licensing of drugs and vaccines for veterinary use. Finally, the consumer expectations for high standards quality of poultry products will strongly influence the production methods. This means that farmers, veterinarians, stockholders and all other partners involved in the production chain will have to share more responsibilities and that cooperation will be intensified.

Conflict of Interest

The authors declared no conflicts of interest.

Authors Contributions

Both authors wrote the main review text and Prof. Hafez Mohamed Hafez read and approved the final manuscript.

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