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# Strategies for Controlling *Campylobacter* in Poultry Production: A Comprehensive Review of Challenges and Potential Solutions

**Tosin Akin Akinmolayan [a], Jude Oluwapelumi Alao [a*], Eunice Damilola Wilkie [a], Daniel Abayomi Odeyemi [b], Taofikat Olatundun Akintoyese [a] and Abosede Yetunde Owolabi [a]**

*[a] Department of Microbiology, Adeleke University, Ede, Nigeria.*
*[b] The School of Medicine, Dentistry and Biomedical Sciences, Faculty of Medicine, Health and Life Sciences, Queen's University Belfast, United Kingdom.*

***Authors' contributions***

*This work was carried out in collaboration among all authors. Author ATA conceptualized the review and wrote the first draft of the manuscript. Authors AJO, WED, ODA, ATO and OAY managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

Campylobacteriosis, a major foodborne illness caused by *Campylobacter*, poses significant challenges in poultry production. This review examines strategies to mitigate *Campylobacter* prevalence and foodborne outbreaks in poultry. Antibiotic therapy is limited due to *Campylobacter*'s antibiotic resistance. Natural alternatives, including bacteriocins, phages, probiotics, essential oils, and plant-derived compounds, show promise in combating *Campylobacter* and improving meat

**Corresponding author: Email: alaojude@adelekeuniversity.edu.ng;*

safety. Biosecurity measures and hygiene practices are crucial in preventing *Campylobacter* introduction and colonization. Strict protocols and cleanliness reduce contamination. Nutritional interventions and vaccination strategies enhance disease resistance and immune responses in poultry. Nanotechnology, particularly ZnO nanoparticles, exhibits antimicrobial efficacy against *Campylobacter* and other bacteria. Electrostatic interaction with cell walls and the production of reactive oxygen species disrupt bacterial membranes and intracellular components. A comprehensive approach integrating natural alternatives, biosecurity, nutrition, and nanotechnology is necessary for effective *Campylobacter* control. Continued research and adherence to hygiene practices can reduce *Campylobacter* contamination, improve food safety, and protect public health.

*Keywords: Campylobacter; transmission; poultry; contamination; campylobacteriosis.*

## 1. INTRODUCTION

The available data indicates that in recent years, Campylobacteriosis incidence has increased in both developed and developing countries [1], with individual cases and outbreaks of the infection common globally. Campylobacteriosis is caused by *Campylobacter spp*., which are the commonest zoonotic pathogens globally. Most *Campylobacter* infections are caused by *Campylobacter jejuni*, and to a lesser extent, *C. coli*.

The name "*Campylobacte*r" [kam″pə-lo-bak′tər] is derived from the ancient Greek meaning "curved rod", where "kampylos" means "curved" and "baktron" means "rod". However, instead of having a curved rod form, *Campylobacter*'s distinctive shape actually resembles a spiral or helical one. To adapt to challenging circumstances, *Campylobacter* may transform its structure into a filamentous or coccoid one [2]. *Campylobacter* was initially identified as a "*Vibrio*-like bacteria" after being isolated from a sheep abortion case [3]; however, after clearly differing in taxonomic profile from the Vibrio species, it was renamed "*Campylobacter*". *Campylobacter* species are highly diverse at the subspecies and strain levels [4]. Diversity involves variances in genetic and phenotypic features, as well as development requirements, which may explain their appearance in different hosts or ecological niches, such as various poultry and wild birds. Some *Campylobacter* species have a single polar flagellum or bipolar flagella (e.g., *C. concisus, C. coli, C. jejuni*, and *C. showae*), whereas others (e.g. *C. ureolyticus* and *C. hominis*) do not [5]. Also, within a location, there might be significant regional variations in *Campylobacter* cases. This is caused by various factors, including underreported cases, limited sensitivity of detection methods, population size and composition, disparities in public health standards, intervention strategies, surveillance systems, food safety norms, and the prevalence of Campylobacter in localised natural reservoirs.

Although *C. jejuni* and *C. coli* are the most prevalent, emerging Campylobacter species been identified to cause infections, including *C. concisus, C. curvus, C. fetus, C. gracilis, C. mucosalis, C. pinnipediorum, C. rectus, C. showae, C. sputorum, C. lari, C. ureolyticus, C. upsaliensis,* and *C. volucris* [6]. The virulence of most emerging *Campylobacter* species are often less severe than those of *C. jejuni* and *C. coli*. Additionally, according to a recent study, *C. concisus* and *C. foetus* infections were more frequent in older people (68.4 years old on average) than in young adults (28.6 years old) [7].

Traveling and person-to-person transfer, close contact with animals, and ingestion of contaminated food or water are a few risk factors that might result in *Campylobacter* infections. According to meta-analysis data, the most important risk factors for *Campylobacter* infections include domestic and international travel, intake of raw chicken, environmental exposure, and close contact with farm animals. Most *Campylobacter* outbreaks are attributed to poultry and untreated water. Poultry, particularly broiler chickens, makes up the majority of the transmission route of this pathogen and presents the primary source of *Campylobacter* transmission in humans. The environment and horizontal transmission between flock mates are the main modes of *Campylobacter* transmission to poultry. If a bird is *Campylobacter* infection positive, all poultry on the same farm will be infected within a week [8]. Poultry and poultry products are an important transmission source because chickens' gastrointestinal tracts contain *Campylobacter*. As a result, the procedures for slaughtering broilers and processing chicken meat constitute a significant threat. They

frequently lead to cross-infection of broiler carcasses due to contamination by intestinal content [9]. Inflammatory reactions, septicemia, Guillain-Barré syndrome (GBS), and other associated symptoms are brought on by *Campylobacter* adhering to and penetrating the intestinal epithelial cell after consumption of the infected broiler meat [10].

The importance of poultry and poultry products in the transmission of *Campylobacter* cannot be overemphasized. Understanding the transmission dynamics of *Campylobacter* species in poultry is important for preventing the infection, and ultimately, conquering Campylobacteriosis. This review consequently covers the transmission of *Campylobacter* in poultry and poultry products.

## 2. CAMPYLOBACTER INFECTION: UNDERSTANDING THE ROLE OF RESERVOIRS AND SOURCES

Since the inception of poultry rearing, poultry has long been recognized as the primary source of *Campylobacter* species transmission to humans through food [11]. *Campylobacter* naturally colonize the cecum of birds and are transmitted among avian populations through the fecal-oral route [11,12]. Additionally, although present in smaller quantities, *Campylobacter* can also be found in the liver and small intestine of birds [11,12].

## 3. ASSESSING THE PREVALENCE AND RISK FACTORS OF CAMPYLOBACTER CONTAMINATION IN POULTRY

In poultry production systems, including those for broilers, layers, turkeys, and ducks, *Campylobacter* is quite common. *Campylobacter* is most typically absent in commercial broilers less than 2-3 weeks old, while experimental inoculation of newly born chicks with *Campylobacter* can effectively establish colonization. The causes of this lag period are unknown, although it might be due to a combination of factors such as maternal antibodies, antibiotic feed additives, intestinal development, and intestinal microbial ecology [45].

In the chicken microbiome, *C. jejuni* is one of the most predominant commensal bacteria. Other *Campylobacter* species like *C. concisus, C. lari,* and *C. upsaliensis* are also common [13]. These bacteria often spread horizontally to flocks from several environmental sources. Campylobacter species have been shown to be prevalent in the environment surrounding chicken farms, including soil, water sources, dust, surfaces, and air. *Campylobacter* can be transmitted from the environment to poultry farms via animal feed and/or drinking water. Farmers and farm visitors who carry *Campylobacter* can spread it to poultry farms. Several investigations identified *Campylobacte*r from wild bird feces near poultry houses, indicating that wild birds helped spread these bacteria into chicken houses. Other species, including as flies, insects, amoebae, yeasts, and molds, have been discovered to be key drivers of *Campylobacter* horizontal transmission into poultry buildings [13]. The presence of amoebae, yeasts, and molds in *Campylobacter* cells allows them to live longer. In poultry facilities, a smaller mealworm beetle and its larvae (*Alphitobius diaperunus*) have been found as major transmitters of *C. jejuni*. They might spread *C. jejuni* not only within batches, but also throughout flocks in subsequent rearing cycles [14]. Furthermore, microbial eukaryotes may operate as a *Campylobacter* reservoir in the environment. Numerous *C. jejuni* strains, for example, may penetrate, multiply, and survive inside an amoeba host (*Acanthamoeba polyphaga*) [14,15]. Because eukaryotes are often found in both drinking water systems and microbial biofilms on farms [14-16], infected eukaryotes may contribute to *C. jejuni* transfer to poultry materials.

There has long been debate about whether *Campylobacter* may be transferred vertically from one generation of poultry to the next. A study of 60,000 progeny parent breeders found no indication of vertical transmission of *Campylobacter* to chickens [17]. However, research has shown that egg passage can result in the transmission of fecal bacteria like *Campylobacter*, which can then infect the shell, shell membrane, and albumen of newly laid and viable eggs [17,18]. This can result in *Campylobacter* ingestion when chicks hatch from their eggs, as well as *Campylobacter* colonization and dissemination in chicken houses. In contrast, *Salmonella* is well-known for vertical transmission because they contaminate the egg within the reproductive canal before the shell is produced or pierce the eggshell and enter the yolk of the post-lay egg. Furthermore, *Salmonella* is the most common cause of

foodborne outbreaks related with chicken eggs, but Campylobacter egg-associated outbreaks are relatively rare [13]. *Campylobacter* was rarely recovered from the internal egg contents, according to a systematic review of 4,316 references [19], which was further verified by multiple on-farm investigations.

## 4. CAMPYLOBACTER COLONIZATION IN CHICKENS

Since *Campylobacter* infection in chicken does not result in a significant inflammatory response or intestinal tissue damage, the slow and moderate *Campylobacter*-specific antibody response is not surprising. The interaction between *Campylobacter* and the chicken immune system that initiates the immune response is still mostly unclear. Developing immunization-based strategies to prevent *Campylobacter* infections in poultry would be substantially aided by understanding the intricate interplay between *Campylobacter* and the chicken immune systems. Young chickens' spleen, liver, and blood were also shown to have *Campylobacter* in certain investigations, which raises the possibility that the pathogen may infiltrate intestinal epithelial cells and spread throughout the body.

In chickens, *Campylobacter* colonization is mainly caused via horizontal transmission from the environment, such as drinking water or animal feed. After one week, *Campylobacter* multiples and colonizes the intestinal tracts (crap, small intestine, and ceca) of the majority of chickens which contract them. *C. jejuni* levels inside these niches might be as high as $10^9$ cells/gram of intestinal tract until slaughter, with no symptoms or evident adverse consequences. According to one study, *C. jejuni* is more than simply a commensal bacterium in broiler chickens; it can also induce chronic inflammation, gut tissue damage, and diarrhea. In contrast, independent of chicken growth rate or breed, four combined and eight individual chicken genotypes revealed no difference or negative effect on *C. jejuni* colonization and proliferation [13].

Several factors influence *Campylobacter* colonization in chickens. These include the chicken strain, the Campylobacter strain, the amount of viable Campylobacter cells, and the season [20]. Under in-vivo experimental conditions, the colonization potential of some *Campylobacter* strains could be increased by 1,000-folds or 10,000-folds, making it difficult to predict the ability of Campylobacter wild strains to colonize chicken flocks in real commercial farms [13]. Summer has a greater rate of colonization than any other season of the year. The amount of colonization and strain type are also seasonally dependent. Aside from high temperatures and humidity, summer requires greater ventilation in poultry buildings, exposing the birds to more Campylobacter from the outside environment than any other time of year [13,21].

Furthermore, geographical regions, flock size, and production system type (i.e., organic or conventional) can all impact *Campylobacter* colonization in chicken flocks [20]. One research found that up to 100% of organic and free-range flocks tested positive for *Campylobacter* [22]. This is most likely due to the birds' exposure to the outdoors environment and the longer time it takes them to reach slaughter size compared to indoor raised flocks. In situations where *Campylobacter* colonization was detected at the species level, *C. jejuni* was the dominant group, colonizing around 90% of Campylobacter-positive birds. *C. coli* and *C. lari* colonized the remaining ones roughly evenly. Several European investigations concluded that the indoor-grown flocks were largely colonized by one or two *C. jejuni* strains. Several *C. jejuni* strains colonized the indoor-grown flocks in other studies conducted in North America and Australia. This might be attributed to various degrees of biosecurity requirements in different nations, as *C. jejuni* colonization can be caused by exposure to several sources containing different strains or a single source containing many strains (e.g., feed or water).

The ability of *Campylobacter* strains to adapt to their environments and their responses thereto is another crucial element in chicken colonization. For instance, *C. jejuni* has a remarkable capacity to change quickly throughout storage, culture, and condition transfer, according to Gaynor and colleagues [23,24]. Before live chickens enter poultry processing plants, certain processes, such as feed withdrawal and transportation, have an impact on the prevalence of *Campylobacter* in the animals. Farmers frequently remove animal feeds from chicken houses 3 to 18 hours before slaughter, a procedure known as "feed withdrawal" [24]. In order to limit cross-contamination during the processing of chicken, this method aims to empty the gastrointestinal tract and lower the amount of fecal matter in the

body. Byrd and colleagues demonstrated that the removal of feed might raise the frequency of *Campylobacter* in broiler chicken crops at the time of slaughter [24]. Whyte and colleagues revealed that poultry overcrowding and stress during transportation significantly increased *Campylobacter* shedding in broiler feces and contributed to cross-contamination of their carcasses during processing [24,25].

## 5. CONTROL OF CAMPYLOBACTERIOSIS IN POULTRY AND POULTRY PRODUCTS

Most poultry with Campylobacteriosis recover without treatment. Although antibiotics are commonly used to kill the bacteria, they cannot completely prevent Campylobacteriosis, and the growing antibiotic resistance of *Campylobacter* poses a global public health concern for both humans and animals. Moreover, antibiotic use in chicken farms can disrupt the gut flora. Therefore, it is crucial to quickly identify natural alternatives that can limit or prevent *Campylobacter* colonization in poultry farms, thus helping to contain outbreaks of foodborne diseases [26].

Recent efforts to manage *Campylobacter* have focused on preventing and reducing its colonization in broiler chicks, as reducing the numbers of *Campylobacter* in broiler carcasses would lead to decreased meat contamination and, consequently, a decline in human Campylobacteriosis. Three main strategies can be identified as fundamental approaches to prevent and control *Campylobacter* prevalence in poultry flocks: (1) implementing biosecurity and hygiene measures to prevent the introduction of Campylobacter to poultry farms; (2) employing nutritional interventions to improve disease resistance and immune responses; and (3) utilizing vaccination interventions to enhance antibody responses and vaccination rates.

Implementing a well-designed biosecurity program at the farm level is a key strategy for combating pathogens like *Campylobacter* in poultry farms [27]. Over the past two decades, there has been an increasing focus on enhancing and advancing biosecurity standards. Previous research has indicated that chicken farms with excellent biosecurity and cleanliness standards tend to have lower levels of Campylobacter colonization. Research conducted over the past 20 years has also explored the use of natural alternatives to prevent and manage *Campylobacter* colonization in poultry farms. These studies have shown that pre-harvest nutritional supplementation with plant-derived compounds, prebiotics, probiotics, bacteriocins, and bacteriophages has significant antibacterial activity against *Campylobacter* and can improve meat safety following processing in slaughterhouses. Similarly, the development of poultry vaccines against *Campylobacter* can help reduce human Campylobacteriosis cases and the prevalence of the bacteria in poultry flocks.

Various control measures have been implemented at different stages of chicken production, including primary production, slaughterhouses, and food processing, with varying degrees of effectiveness.

## 6. ON-FARM INTERVENTIONS TO CONTROL CAMPYLOBACTER COLONIZATION IN POULTRY

In recent years, early-stage on-farm management of *Campylobacter* in broiler chickens has received increased attention due to the successful colonization of chickens by *Campylobacter* from the earliest stages of their lives, as well as its persistence throughout the poultry processing line. Various control options, such as phage treatment, bacteriocins, probiotics, fatty acids, and essential oils, have been studied for their potential in managing *Campylobacter* (Table 1).

Bacteriocins, which are antimicrobial peptides produced by commensal bacteria in the chicken gut microbiota, have shown promise in inactivating Campylobacter both in vitro and in vivo. For instance, the bacteriocin L-1077 was found to significantly reduce *C. jejuni* numbers (>4 log CFU/g) in cecal content [28]. Another study investigated the development of *C. jejuni* resistance through oral administration of three different bacteriocins from *Lactobacillus salivarius* (OR-7) and *Enterococcus faecium* (E-760 and E50-52) in broiler chickens [29]. The CmeABC multidrug efflux pump in *C. jejuni* was found to play a critical role in both innate and acquired resistance to bacteriocins. To effectively inactivate *C. jejuni* and prevent the emergence of antibiotic resistance, the use of bacteriocins and efflux pump inhibitors may be considered.

**Table 1. The advantages and disadvantages of various Campylobacter preventive and control measures in chicken production (Adapted from [13])**

| Strategies | Advantage | Disadvantage |
|---|---|---|
| Bacteriocins | Reduced *C. jejuni* by more than >4 log CFU/g in in-vitro conditions. [28] | Antimicrobial resistance is being developed via the CmeABC multidrug efflux pump. [29] |
| Bacteriophages | *C. jejuni* levels in commercial broiler flocks were reduced by up to 5 log CFU/g. [30] | Over time, gastrointestinal dilution and resistance development [31] |
| Probiotics | A portion of the microbiota of chicken gut [1] | *C. jejuni* decrease was limited after 15 days of oral administration [32] |
| Short chain fatty acids | Capability to penetrate gut epithelial cells [33] | The reduction of *C. jejuni* under in-vitro settings is limited [33] |
| Vaccination | Prophylactic and promising [34] | Expensive, demanding, and very specific [1] |

The effectiveness of *Campylobacter* phages in reducing the number of *Campylobacter* or preventing their colonization in chicken broilers has also been investigated in several studies. In one study, using an artificial infection model and a highly colonizing strain of *C. jejuni*, numerous phages isolated from the same environment as the bacterial host showed significant reductions [36]. Some phages, when applied at a high Multiplicity of Infection, led to up to 3 log reductions within the first 24 hours, while others resulted in approximately a 1 log decrease for up to 30 days (MOI).

## 7. CAMPYLOBACTER CONTAMINATION IN POULTRY PROCESSING FACILITIES

Chicken meat is considered a sustainable primary source of dietary protein due to its significantly lower feed conversion ratio (FCR) compared to beef. With an FCR of around 40%, chicken is highly efficient in converting feed into edible weight. However, poultry production, which involves animal farming and food processing, is also a common source of foodborne outbreaks, with live chickens and poultry meat serving as important reservoirs for *Campylobacter* and other foodborne pathogens [1]. Implementing effective on-farm and in vivo *Campylobacter* control measures is challenging due to the complexity and diversity of the industry (Table 2).

The processing of poultry is a labor-intensive operation that requires well-trained employees. Any lapse in sanitation or hygiene standards can result in multiple cases of foodborne diseases. *Campylobacter*, present in the cecal content at levels up to $10^9$ cells/g, can enter a processing facility through potentially infected birds [13]. Birds from different farms, with variations in age, size, geographical origin, production methods, and biosecurity practices, are typically processed together, increasing the risk of *Campylobacter* contamination. The processing procedures, including receiving, hanging, and packing, involve various stages where *Campylobacter* can start to proliferate or contaminate chicken carcasses (Table 2). Processes such as scorching, defeathering, evisceration, nick removal, and inside-out washing can all contribute to the cross-contamination of *Campylobacter spp*.

Evisceration, in particular, is a critical step for cross-contamination. The densely populated *Campylobacter* present in the gastrointestinal tract of poultry birds can spread extensively, especially in cases of gut leakage. Numerous in-plant studies have shown a significant increase in the prevalence of *Campylobacter*-positive carcasses after the evisceration process [36]. During evisceration, when birds are typically hung upside-down by their feet, *Campylobacter* leakage from the stomach can contaminate the lower half of the carcasses (breast and neck) more than the upper half (thighs and drumstick). *Campylobacter* is frequently detected in the hanging necks of the carcasses [13].

To prevent bacterial growth after evisceration, rapid cooling of poultry carcasses is crucial. Many processing facilities use a combination of chilling and antimicrobial treatment by washing the carcasses with cold chlorinated water to conserve energy and inhibit bacterial development [36]. Additionally, after evisceration, poultry carcasses are often cleaned by dipping or spraying them in chlorinated water to remove contaminants, blood, tissues, and fragments. However, under commercial processing

**Table 2. Examples of *Campylobacter* prevalence and load across the chicken processing chain. (Adapted by [13])**

| Stage | Source | *Campylobacter* prevalence (%) and/or average load | Reference |
|---|---|---|---|
| Plant | Pre-scald | 77%, > 6 log CFU/g of feather or skin (*n* = 40) | [38] |
| | Defeathering | 3.9 log CFU/ml of carcasses rinse (*n* = 24) | [39] |
| | Evisceration | 96–100%, 2.7 log CFU/carcass (*n* = 48) | [40] |
| | Pre-chill | 98%, 4.75 log CFU/ml of carcasses rinse (*n* = 450) | [41] |
| | Post-chill | 84.7%, 3.03 log CFU/ml of carcasses rinse (*n* = 450) | [41] |
| | Pre-wash | 87%, 4.78 log CFU/ml of carcasses rinse (*n* = 30 [4 processing plants]) | [42] |
| | Post-wash | 80%, 4.30 log CFU/ml of carcasses rinse (*n* = 30 [4 processing plants]) | [42] |
| Retail | | 90%, > 4 log CFU/carcass (*n* = 552) | [43] |

conditions, dipping can lead to cross-contamination of carcasses, especially when a large number of birds are processed simultaneously [37].

## 8. TREATMENT OF POULTRY PLANTS USING ANTIMICROBIALS

Numerous studies have investigated the efficacy of various permitted antimicrobials, including chlorine, chlorite, acidified sodium, cetylpyridinium, trisodium phosphate, chlorine dioxide, and peroxyacetic acid, in reducing the levels of *Campylobacter* in chicken meat by up to 5 logs. However, despite the effectiveness of these antimicrobials, the temperature of the water, or the washing mechanism employed, in-plant poultry washers have demonstrated limited capability in inactivating *Campylobacter* in chicken meat.

This limited effectiveness can be attributed to several factors. Firstly, chicken meat contains large molecules such as proteins and lipids, which may hinder the action of antimicrobials and prevent their full penetration into the meat. Additionally, changes induced by processing, the sensitivity of chicken skin to heat, oxidation, and discoloration, as well as the initial microbial load of carcasses, can contribute to the survival of *Campylobacter* despite washing treatments. The number of processed carcasses per minute, as well as the interaction or masking of antimicrobials, such as chlorine, by organic materials present in the processing water, can further impact their efficacy. Moreover, the quality of the water used during processing and the ability of *Campylobacter* to survive under certain conditions are also influential factors.

It is important to highlight that unlike the pasteurization stage in the processing of milk, there is no single effective critical control point for killing *Campylobacter* during the processing of raw chicken [2]. This emphasizes the need for comprehensive approaches and multiple interventions throughout the poultry processing chain to address *Campylobacter* contamination effectively.

## 9. ALTERNATIVE CONTROL STRATEGIES FOR CAMPYLOBACTER CONTAMINATION IN AGRI-FOODS

The use of herbs and essential oils in medicine initially stemmed from their beneficial properties such as antibacterial, anti-inflammatory, and antioxidant effects. Over time, these compounds found their way into the agricultural and food industry during the nineteenth century, primarily for their aromatic qualities and flavor profiles. These antimicrobials are classified as secondary metabolites and serve as essential components in plant defense systems, aiding in the protection against microbial diseases [38].

In addition to their antimicrobial properties, essential oils can also act as growth promoters in agricultural animals, similar to antibiotics [39]. A histology study demonstrated that feeding various plant extracts to chicken broilers resulted in a thickened mucus layer in their glandular stomach and jejunum [40]. This modification in the gastrointestinal tract was associated with a significant alteration in the gut microbiome, which has the potential to promote the growth and development of birds.

Several plants have been scientifically proven to possess anti-Campylobacter properties. For instance, cinnamon, which encompasses approximately 250 different species within the

*Cinnamomum* genus, exhibits antimicrobial activity against *Campylobacter*. Another plant with anti-*Campylobacter* potential is turmeric (*Curcuma longa*), which contains curcumin as its major active compound. These examples highlight the diverse range of plants that hold promise in combating *Campylobacter* contamination.

## 10. NANOPARTICLES OF METAL OXIDE

In recent times, there has been a significant interest in exploring new applications of nanotechnology and nanomaterials. One area of focus is the utilization of metal oxide nanoparticles (such as $Al_2O_3$, $TiO_2$, and ZnO NPs) to deactivate various pathogens responsible for foodborne illnesses in different agri-food systems [41]. Studies have demonstrated that ZnO nanoparticles exhibit greater effectiveness against both Gram-negative and Gram-positive bacteria compared to other metal oxides like CuO and $Fe_2O_3$ [42]. Moreover, ZnO NPs have shown superior anti-*C. jejuni* properties compared to other Gram-negative bacteria like *E. coli* O157:H7 and *S. enterica* [43].

The direct electrostatic interaction between positively charged ZnO nanoparticles and the negatively charged bacterial cell wall leads to the destabilization and disruption of the bacterial outer cell membrane. Furthermore, ZnO's semiconductive nature allows the generation of reactive oxygen species, which can attach to and attack various cytoplasmic and extracellular targets [44]. These mechanisms contribute to the antimicrobial action of ZnO nanoparticles against *Campylobacter* and other pathogens.

## 11. CONCLUSION

Addressing the challenges of *Campylobacter* in poultry production and the associated foodborne outbreaks requires a comprehensive and multi-faceted approach. Strategies such as natural alternatives, biosecurity measures, nutritional interventions, and vaccinations have been investigated to minimize *Campylobacter* contamination and ensure food safety. Bacteriocins, phages, and antimicrobials have shown promise in reducing *Campylobacter* levels in chicken meat, although their effectiveness can be influenced by complex on-farm and in vivo controls, processing-related cross-contamination, and the presence of organic materials.

Emerging technologies, particularly nanotechnology, offer potential solutions. Metal oxide nanoparticles, especially ZnO nanoparticles, exhibit antimicrobial properties against *Campylobacter* and other bacteria. Through electrostatic interaction with bacterial cell walls and the generation of reactive oxygen species, ZnO nanoparticles disrupt bacterial membranes and attack intracellular targets. Further exploration and development of nanomaterial-based approaches hold promise for *Campylobacter* control in the future.

To achieve safer poultry production and reduce the risk of Campylobacteriosis outbreaks, a continuous focus on research, technological advancements, and strict adherence to hygiene and biosecurity practices is crucial. Implementing preventive measures throughout the entire production process, from farm to fork, is essential. This includes optimizing the application of antimicrobial agents, improving processing techniques, and ensuring proper handling and sanitation practices.

By integrating these measures, we can effectively combat *Campylobacter* and minimize the occurrence of foodborne illnesses. This comprehensive approach safeguards both human and animal health and contributes to the sustainability and safety of the poultry industry. Continued efforts in research and the adoption of innovative strategies will pave the way for a future where *Campylobacter*-related risks are mitigated, ensuring the well-being of consumers and the industry as a whole.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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