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Comparative Evaluation of Zinc Oxide and Thyme Essential Oil Nanoparticles as Antimicrobial Agents Against *Campylobacter jejuni* in Food Products

Alhanouf S. Almutairi[1], Marwa Abd Elhamed[2], Hossam E. Ghaneem[3] and Mona M. Sobhy[4]*

[1]Saudi Ministry of Health, Hafr Al-Batin, Kingdom of Saudi Arabia

[2]Egypt Center for Research and Regenerative Medicine, Cairo, Egypt

[3]Scientific Center for Research and Training in Sadat City (SCRT), Egypt

[4]Department of Reproductive Diseases, Animal Reproduction Research Institute ARC, Giza, Scientific Center for Research and Training in Sadat City (SCRT), Egypt

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***Correspondence:**
Mona M. Sobhy, Department of Reproductive Diseases, Animal Reproduction Research Institute ARC, Giza, Scientific Center for Research and Training in Sadat City (SCRT), Egypt,
E-mail: monagabr17@yahoo.com

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Abstract

Campylobacter jejuni is a leading cause of foodborne gastroenteritis worldwide, commonly associated with contaminated meat and poultry products. This study aimed to investigate the incidence of *C. jejuni* in various food samples, evaluate the antimicrobial activity of Zinc Oxide Nanoparticles (ZnO-NPs) and thyme essential oil nanoparticles, and characterize key virulence genes among the isolates. A total of 1,060 samples, including meat products, dairy products, and food handlers, were examined. The overall incidence of *C. jejuni* was 11.13%, with the highest prevalence observed in sausages (32.14%), followed by burgers (21.00%) and shawarma meat (18.75%). Lower incidence rates were detected in yogurt (9.23%) and ice cream (13.85%), while food handlers showed a contamination rate of (25.00%), indicating their potential role in cross-contamination. Molecular analysis confirmed the presence of virulence-associated genes, with *cadF* (75%) being the most prevalent, followed by *cdtB* (60%) and *flaA* (33%), indicating varying pathogenic potential among isolates. The antimicrobial activity assessment revealed that ZnO-NPs exhibited a concentration-dependent inhibitory effect, achieving complete inhibition at 1 mL, whereas partial inhibition was observed at lower concentrations. In contrast, thyme essential oil nanoparticles demonstrated superior efficacy, completely inhibiting *C. jejuni* growth at all tested concentrations. In conclusion, thyme essential oil nanoparticles showed greater antimicrobial effectiveness compared to ZnO-NPs and represent a promising natural strategy for controlling *C. jejuni* in food systems. The detection of key virulence genes further highlights the public health risk associated with contaminated food products. These findings support the application of nanotechnology-based interventions to enhance food safety, although further studies are needed to evaluate their safety and practical implementation.

Keywords: *Campylobacter jejuni*; ZnO Nanoparticles; Thyme Oil; Antibacterial Activity; Food Contamination; Nanomaterials

Introduction

Foodborne pathogens continue to represent a major global challenge in food safety and public health, particularly those associated with poultry and meat products. Among these, *Campylobacter jejuni* is recognized as one of the leading causes of bacterial gastroenteritis worldwide and is responsible for a substantial proportion of foodborne infections in humans [1, 2]. Infection is primarily linked to the consumption of contaminated or undercooked poultry products, raw milk, and cross-contaminated food. Clinical manifestations range from self-limiting diarrhea to severe inflammatory enteritis, and in some cases may lead to post-infectious complications such as Guillain-Barré syndrome [3]. Recent reports continue to highlight its persistence in food chains and its ability to form biofilms, which enhances survival and transmission under harsh environmental conditions [4].

The increasing prevalence of Antimicrobial Resistance (AMR) among *C. jejuni* strains has significantly reduced the effectiveness of conventional antibiotic therapies, raising serious concerns for both clinical treatment and food safety management [5]. Recent genomic surveillance studies have confirmed the spread of resistance determinants such as *gyrA* and *tet(O)* genes, indicating

an ongoing global evolution of resistant Campylobacter populations and a projected increase in disease burden if alternative interventions are not implemented [6]. Therefore, the development of novel, safe, and effective antimicrobial strategies for food decontamination is urgently required.

Nanotechnology has emerged as a promising approach in food microbiology due to the unique physicochemical and biological properties of nanoparticles, including their high surface area, enhanced reactivity, and ability to interact directly with microbial cell structures. In food systems, nanomaterials have demonstrated significant potential in improving food safety, extending shelf life, and reducing microbial contamination [7]. Metal oxide nanoparticles, particularly zinc oxide nanoparticles (ZnO-NPs), have gained considerable attention due to their broad-spectrum antimicrobial activity. Their mechanisms of action include the generation of Reactive Oxygen Species (ROS), disruption of bacterial cell membranes, and release of zinc ions, which interfere with essential cellular processes [8]. Recent studies have demonstrated the effectiveness of ZnO-based systems in controlling *C. jejuni* contamination in food matrices such as poultry products [9].

In parallel, plant-derived essential oils have been widely investigated as natural antimicrobial agents. Thyme essential oil is particularly notable due to its high content of bioactive compounds such as thymol and carvacrol, which exhibit strong antibacterial and antibiofilm activities [10]. However, the direct application of essential oils is limited by their volatility, poor water solubility, and chemical instability. Recent advances in nanotechnology have enabled the encapsulation of essential oils into nanoparticle systems, significantly improving their stability, bioavailability, and antimicrobial efficiency [11]. Thyme-based nano formulations have shown promising activity against foodborne pathogens, including *C. jejuni*, and enhanced controlled release properties compared to free oils [12].

Despite growing evidence supporting the individual antimicrobial potential of ZnO nanoparticles and plant-based nano-encapsulated essential oils, comparative studies evaluating their efficacy against *Campylobacter jejuni* in real food systems remain limited [13]. Therefore, this study aims to comparatively evaluate the antimicrobial activity of zinc oxide nanoparticles and thyme essential oil nanoparticles against *C. jejuni* in contaminated food products. The findings are expected to provide insights into their potential application as alternative antimicrobial agents for improving food safety and reducing foodborne disease risk.

Materials and Methods

Distribution of examined food samples

A total of 1,060 samples comprising different food products and food handlers were examined for the presence of *Campylobacter jejuni* (Table 1). The collected samples included both ready-to-eat and raw food items. Samples were transported to the laboratory in insulated ice boxes (4±1°C) and processed within 4 h of collection. Each sample was homogenized (25 g) in 225 mL of sterile buffered peptone water using a stomacher for microbiological analysis.

Isolation and Identification of *Campylobacter jejuni*

Isolation of *C. jejuni* was performed according to [14]. guidelines. Briefly, enriched samples were inoculated onto modified Charcoal Cefoperazone Deoxycholate Agar (mCCDA) and incubated under microaerophilic conditions (5% O_2, 10% CO_2, 85% N_2) at 42°C for 48 h. Suspected colonies were identified based on morphological characteristics and further confirmation was carried out using biochemical assays and/or PCR targeting species-specific genes (e.g., *hipO* gene).

Table 1: Distribution of examined food samples for the isolation of *Campylobacter jejuni*.

Food Samples	No. of samples
Grilled chicken	200
Shawarma of chicken	150
Shawarma of meat	160
Burger	100
Sausages	140
Kofta	120
Ice-cream	65
Yogurt	65
Food Handlers	60
Total	**1060**

Table 2: Primers of virulence genes.

Gene	Primer Sequence (*5′–3′*)	Product Size
cadF	*F: TTGAAGGTAATTTAGATATG*	400 bp
	R: CTAATACCTAAAGTTGAAAC	
flaA	*F: ATGGGATTTCGTATTAACAC*	1728 bp
	R: CTGTAGTAATCTTAAAACATTTTG	
cdtB	*F: GTTAAAATCCCCTGCTATCAACCA*	495 bp
	R: GTTGGCACTTGGAATTTGCAAGGC	

Molecular detection of virulence genes in *Campylobacter jejuni*

Detection of virulence genes by PCR:

The confirmed Campylobacter jejuni isolates were further screened for the presence of key virulence genes, including *cadF*, *flaA*, and *cdtB*, using conventional PCR.

These genes were selected due to their critical roles in pathogenicity:

- *cadF* → adhesion to intestinal epithelial cells
- *flaA* → motility and colonization
- *cdtB* → toxin production (cytolethal distending toxin) (Table 2).

PCR reaction mixture:

PCR amplification was performed in a total volume of 25 μL containing:

- 12.5 μL PCR Master Mix
- 1 μL of each primer (10 pmol)
- 2 μL DNA template
- 8.5 μL nuclease-free water

PCR cycling conditions:

The amplification conditions were as follows:

Initial denaturation: 95°C for 5 min

35 cycles of:

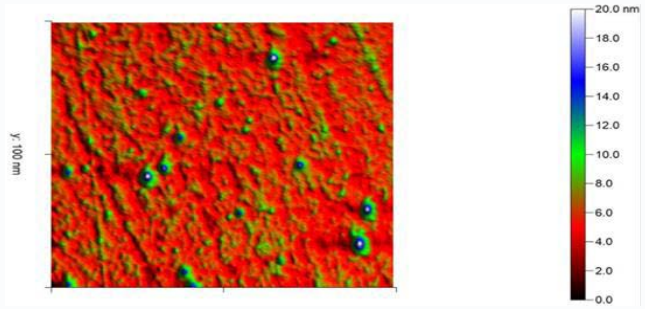

Figure 1: Illustrated the AFM image pf ZnO nanoparticles.

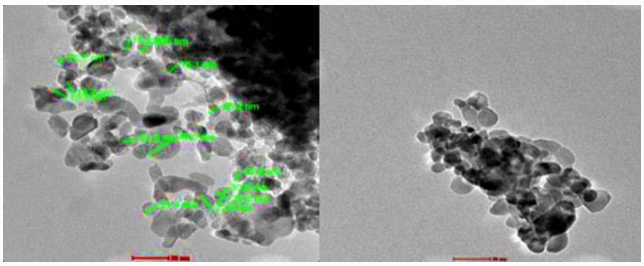

Figure 2: Scanning Electron Microscopy (SEM) of Zinc Oxide nanoparticles (ZnO-NPs) (X3000); Transmission Electron Microscopy (TEM) of ZnO-NPs (20 μg/ml).

Denaturation: 94°C for 30 s

Annealing: 55-58°C for 30 s (depending on gene)

Extension: 72°C for 45-60 s

Final extension: 72°C for 7 min

Agarose gel electrophoresis:

PCR products were separated using 1.5% agarose gel electrophoresis, stained with ethidium bromide, and visualized under UV light. A 100 bp DNA ladder was used to determine fragment sizes.

Acquisition of ZnO-NPs

ZnO-NPs were obtained from Dr. Abdel Salam Al-Muhammady in Arab Center for Nanotechnology, Cairo University. Transmission Electron Microscopy (TEM) HITACHI H800 (Hitachi) and Scanning Electron Microscopy (SEM) (Joe, JSM-5600LV, Japan) were carried out to measure and observe the size and morphology of ZnO-NPs. Microscopy (SEM and TEM) confirmed the formation of triangular and hexagonal-shaped ZnO-NPs with a size range of 2.0-20.0 nm. Scanning by electron microscope (JEOL 6380A; Tokyo, Japan) used to record the micrograph images of synthesized ZnO-NPs (Figure 1,2 & 3).

Preparation of thyme essential oil nanoparticles

Herbal oil of thyme NPs. 10% (*Thymus vulgaris L*) used in this study was purchased from Animal Health Research Institute (AHRI) stored in amber-colored bottles at 4°C until use.

Preparation of aqueous extracts of thyme: In a 250 ml flask, water extract was made by combining 20 g of each dried spice with 100 ml of sterile distilled water. The blend was vigorously stirred and left to filter for 24 hours in a temperature of 25.4°C. To prepare hot water extracts, 20g of each dried spice was combined with (100 ml) of sterilized distilled water in a (250 ml) flask, and the mixture was boiled

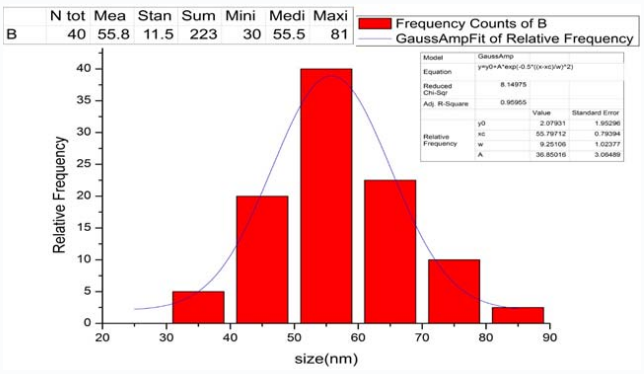

Figure 3: Zinc nanoparticles (ZnO-NPs) with a size range of 20-90 nm.

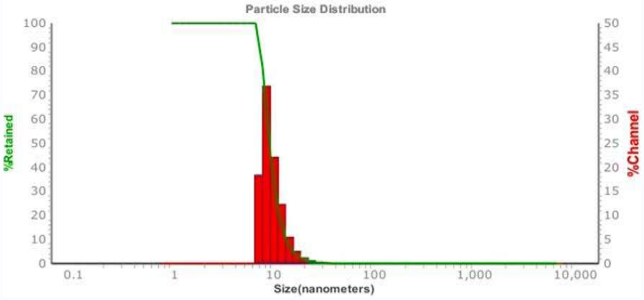

Figure 4: Size of thyme oil nanoparticles.

for 15 minutes to extract the flavors typical cooking conditions. The supernatant was centrifuged after being passed through muslin cloth (30000g, 15 min). Tween (80) was obtained from the (Sigma-Aldrich Co) [15].

Characterization of nano-thyme oil: The nano emulsion was prepared in the Nanomaterials Research and Synthesis Uni t in AHRI by using oils (10 ml) thyme oils Tween 80 (30 ml), and distilled deionized water (50 ml) were mixed for half hour in a homogeneous blender 1500 watt, and then distilled water was slowly added to the mixed oil phase according to [16]. The molecular characterization of thyme oil NPs. presented in (Figure 4) was defined using ATR-FTIR spectroscopy (Figure 4).

Characterization of nanoparticles

Nanoparticles were characterized for:

- Particle size and distribution using Dynamic Light Scattering (DLS)
- Morphology using Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM)
- Zeta potential for stability assessment
- Chemical composition using Fourier Transform Infrared Spectroscopy (FTIR)

Antimicrobial activity assay

The antimicrobial activity of ZnO-NPs and thyme oil nanoparticles against *C. jejuni* was evaluated using:

Agar well diffusion method: Bacterial suspensions were adjusted to 0.5 McFarland standard and spread on Mueller-Hinton agar supplemented with 5% blood. Wells were filled with different

concentrations of nanoparticles. Plates were incubated under microaerophilic conditions at 42°C for 24-48 h, and inhibition zones were measured.

Minimum Inhibitory Concentration (MIC): MIC was determined using the broth microdilution method in 96-well plates. Serial dilutions of nanoparticles were prepared, inoculated with bacterial suspension, and incubated under microaerophilic conditions. The lowest concentration showing no visible growth was recorded as MIC.

Application in food samples

Food samples were artificially inoculated with *C. jejuni* (~10^6 CFU/g) and treated with different concentrations of ZnO-NPs and thyme oil nanoparticles. Samples were stored under refrigeration, and bacterial counts were determined at defined intervals using plate count methods.

Microbiological analysis

Bacterial enumeration was performed using selective media, and results were expressed as log CFU/g. Reduction percentages were calculated to evaluate antimicrobial effectiveness.

Statistical analysis

All experiments were conducted in triplicate. Data were analyzed using one-way ANOVA followed by post hoc tests to determine significant differences ($p < 0.05$). Statistical analysis was performed using software such as SPSS or GraphPad Prism.

Results

Incidence of *Campylobacter jejuni* in examined samples

Out of the total 1,060 examined samples, 118 samples were positive, giving an overall incidence rate of 11.13% for *Campylobacter jejuni* (Table 2). The highest incidence was recorded in sausages, with 45 positive samples out of 140 (32.14%), followed by burger samples (21/100; 21.00%) and shawarma of meat (30/160; 18.75%). Moderate contamination levels were observed in grilled chicken (24/200; 12.00%) and shawarma of chicken (16/150; 10.67%). Lower incidence rates were detected in kofta (15/120; 12.50%) and food handlers (15/60; 25.00%), indicating a possible role of human handling in cross-contamination. Dairy products showed comparatively lower contamination, with ice cream (9/65; 13.85%) and yogurt (6/65; 9.23%) (Table 3 and 4).

Comparative distribution of contamination

Overall, meat and poultry products exhibited higher contamination rates compared to dairy products. The notably high prevalence in processed meat products such as sausages and burgers suggests potential contamination during processing, handling, or storage.

The detection of *C. jejuni* among food handlers (25.00%) highlights their potential role as a critical source of contamination, emphasizing the importance of hygiene practices in food safety systems (Figure 5).

Implications for *Campylobacter jejuni* surveillance

The diversity and distribution of the collected samples reflect the major potential routes of *C. jejuni* contamination in food systems. The predominance of poultry-based products, particularly grilled chicken and chicken shawarma, highlights their epidemiological importance as primary reservoirs of *Campylobacter* spp.

Table 3: Incidence of *Campylobacter jejuni* in examined food samples.

Food Sample	No. Examined	No. Positive	Incidence (%)
Grilled chicken	200	24	12.00
Shawarma chicken	150	16	10.67
Shawarma meat	160	30	18.75
Burger	100	21	21.00
Sausages	140	45	32.14
Kofta	120	15	12.50
Ice cream	65	9	13.85
Yogurt	65	6	9.23
Food handlers	60	15	25.00
Total	**1060**	**118**	**11.13**

Table 4: Biochemical tests for detection of C*ampylobacter jejuni.*

Characteristics	*C. jejuni*
Oxidase	+
Catalase	+
Nitrate reduction	+
Urease	--
Hippurate hydrolysis	+
Growth at:	--
37°C	+
43°C	+
Growth at 1% glycine	+
Susceptibility to:	--
Nalidixic acid	S
Cephalothin	R

Table 5: Prevalence of virulence genes in *Campylobacter jejuni* isolates.

Virulence Gene	Function	Prevalence (%)
cadF	Adhesion	75%
flaA	Motility	33%
cdtB	Toxin production	60%

Molecular detection of virulence genes

PCR analysis of the confirmed *Campylobacter jejuni* isolates revealed the presence of key virulence-associated genes with varying prevalence rates. The *cadF* gene was detected in 75% of the isolates, representing the highest frequency among the tested genes. The *cdtB* gene was identified in 60% of the isolates, indicating a considerable proportion of strains possessing toxin-producing capability. In contrast, the *flaA* gene was detected in 33% of the isolates, reflecting a comparatively lower prevalence of motility-associated factors (Table 5, Figure 6 and 7).

Antimicrobial activity of nanoparticles against *Campylobacter jejuni*

The antimicrobial activity of Zinc Oxide Nanoparticles (ZnO-NPs) and thyme essential oil nanoparticles was evaluated against *Campylobacter jejuni* at different concentrations. Zinc oxide nanoparticles exhibited a concentration-dependent inhibitory effect. Complete inhibition of *C. jejuni* growth was observed at a concentration of 1 mg/mL, indicating strong bactericidal activity. However, at lower concentrations (0.25 mg/mL and 0.50 mg/

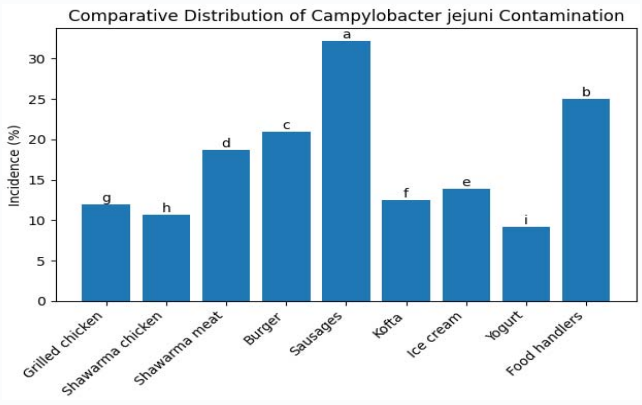

Figure 5: Comparative distribution of *C. jejuni* incidence (%) among different food samples. Different letters indicate variation among sample categories.

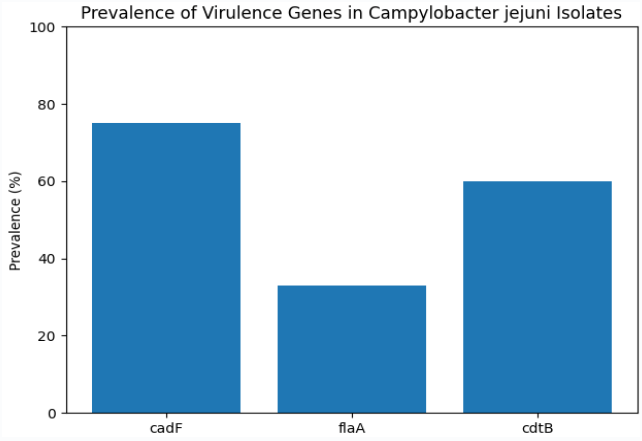

Figure 6: Prevalence of virulence genes (*cadF, flaA,* and *cdtB*) among *Campylobacter jejuni* isolates.

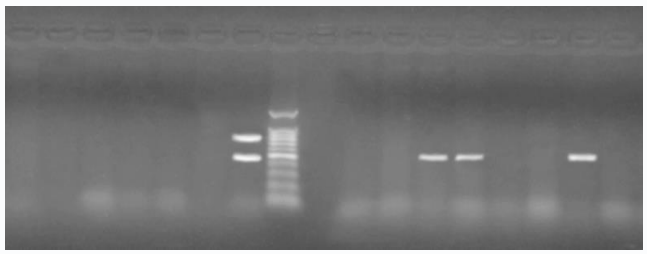

Figure 7: The virulence strains of *C. jejuni* showed M: marker 400-1000bp; Lane 3,4 *CadF* at 400 bp; Lane 7 *CdtB* at 495bp; N: Negative control and P: positive control.

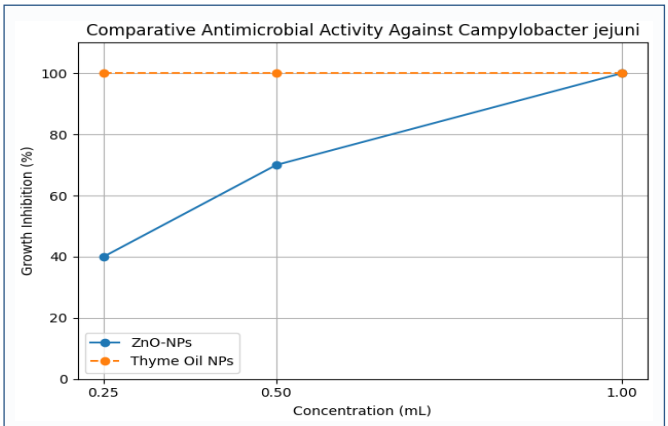

Figure 8: Comparative antimicrobial activity of zinc oxide nanoparticles (ZnO-NPs) and thyme essential oil nanoparticles against *Campylobacter jejuni* at different concentrations.

mL), only partial inhibition was detected, suggesting reduced antibacterial efficacy at suboptimal doses. In contrast, thyme essential oil nanoparticles demonstrated remarkably higher antimicrobial activity, as no bacterial growth was observed even at the lowest tested concentration (first dilution). This indicates that thyme oil nanoparticles possess a more potent inhibitory effect against *C. jejuni* compared to ZnO-NPs under the tested conditions.

Comparative antimicrobial efficacy

A comparative analysis revealed that while ZnO-NPs required higher concentrations to achieve complete inhibition, thyme essential oil nanoparticles exhibited complete suppression of *C. jejuni* growth across all tested concentrations. This suggests that the antimicrobial compounds present in thyme oil, such as thymol and carvacrol, play a critical role in enhancing antibacterial activity when formulated at the nanoscale (Figure 8).

Discussion

The present study confirms that *Campylobacter jejuni* remains a significant foodborne pathogen, particularly in meat and poultry products. The observed overall incidence (11.13%) and higher contamination in processed meat products such as sausages and burgers are consistent with recent findings highlighting the persistence of *C. jejuni* in food chains and its ability to survive through biofilm formation and environmental stress conditions [17].

As illustrated in figure 5, the distribution of contamination varied among food categories, with sausages (32.14%) and burger samples (21.00%) exhibiting the highest incidence rates. This pattern suggests that processed meat products are more susceptible to contamination, likely due to multiple handling steps, increased surface area, and potential cross-contamination during preparation and storage [18].

Furthermore, figure 5 demonstrates a notable contamination level among food handlers (25.00%), reinforcing their critical role as a source of cross-contamination. This finding aligns with previous reports emphasizing the importance of hygiene practices and proper food handling to reduce the transmission of Campylobacter spp. In contrast, dairy products such as yogurt and ice cream showed relatively lower contamination rates, which may be attributed to thermal processing, although post-processing contamination cannot be excluded [19]. The molecular analysis of *Campylobacter jejuni* isolates in the present study revealed a high prevalence of key virulence-associated genes, particularly *cadF* (75%), followed by *cdtB* (60%) and *flaA* (33%), indicating varying degrees of pathogenic potential among the recovered strains. These findings confirm that *C. jejuni* possesses a complex set of virulence determinants that contribute to its ability to colonize, invade, and damage host tissues.

The *cadF* gene, detected in the majority of isolates, plays a critical role in bacterial adhesion to intestinal epithelial cells, representing an essential step in colonization [20]. The high prevalence observed in this study is consistent with recent reports indicating that adhesion-related genes such as *cadF* are widely distributed among *C. jejuni* isolates from food and animal sources. In some studies, *cadF* has been detected in nearly all isolates, emphasizing its importance

as a conserved virulence marker [21]. The *cdtB* gene, responsible for encoding the cytolethal distending toxin, was detected in 60% of isolates, indicating the presence of toxigenic strains capable of inducing host cell damage. This toxin interferes with host cell cycle progression and contributes to gastrointestinal pathology. Recent studies have reported high prevalence rates of *cdtB* and related toxin genes in *C. jejuni* isolates, supporting their central role in pathogenicity and disease severity [22]. In contrast, the *flaA* gene, associated with motility and colonization, was detected at a lower frequency (33%) in the present study. This is relatively lower compared to other reports where *flaA* is frequently detected in a higher proportion of isolates. For example, previous studies have reported detection rates exceeding 60-70%, reflecting its importance in bacterial motility and host colonization. The lower prevalence observed in this study may indicate genetic variability among isolates or differences in environmental adaptation [23].

The variation in the distribution of these virulence genes highlights the heterogeneity of *C. jejuni* strains circulating in food systems. Recent reviews emphasize that *C. jejuni* pathogenicity is multifactorial, involving a combination of adhesion, motility, and toxin production mechanisms that enable the bacterium to survive and persist in diverse environments [24]. The coexistence of multiple virulence genes within the same isolates enhances their ability to cause infection and increases their public health significance [25]. The antimicrobial evaluation revealed distinct differences between Zinc Oxide Nanoparticles (ZnO-NPs) and thyme essential oil nanoparticles. As shown in figure 8, ZnO-NPs exhibited a clear concentration-dependent inhibitory effect, with partial inhibition observed at lower concentrations (0.25 and 0.50 mL) and complete inhibition achieved only at 1 mL. This behavior is consistent with the known antimicrobial mechanisms of ZnO-NPs, including Reactive Oxygen Species (ROS) generation, membrane disruption, and Zn^{2} ion release [26]. The comparative trends illustrated in figure 8 clearly indicate that while ZnO-NPs require higher concentrations to achieve full antimicrobial activity, thyme essential oil nanoparticles are effective even at minimal concentrations. This highlights the potential of plant-based nano-antimicrobials as more efficient alternatives for controlling foodborne pathogens in food systems [9, 27].

In contrast, thyme essential oil nanoparticles demonstrated superior antimicrobial efficacy, as evidenced in figure 8, where complete inhibition of *C. jejuni* was observed across all tested concentrations. This suggests a stronger and more immediate antibacterial effect compared to ZnO-NPs. The enhanced performance of thyme nanoparticles can be attributed to the presence of bioactive compounds such as thymol and carvacrol, which are known to disrupt bacterial membranes, increase permeability, and inhibit essential enzymatic functions [28]. The high antimicrobial efficiency of thyme oil is mainly attributed to bioactive compounds such as thymol and carvacrol, which disrupt bacterial membranes, increase permeability, and inhibit enzymatic activity [29].

From a practical perspective, the findings presented in figure 5 and 8 collectively demonstrate that high-risk food categories, particularly processed meat products, can benefit significantly from nanoparticle-based antimicrobial interventions. The superior performance of thyme essential oil nanoparticles suggests their potential application as natural, safe, and effective preservatives in food safety systems [30]. This suggests that combining inorganic nanoparticles with plant-derived bioactive compounds could provide a more effective strategy for controlling foodborne pathogens [10]. From a mechanistic perspective, the superior performance of thyme oil nanoparticles observed in the current study may be explained by their enhanced bioavailability, stability, and controlled release properties at the nanoscale, which facilitate stronger interactions with bacterial cells [31]. Meanwhile, ZnO-NPs rely more on physicochemical interactions and oxidative stress, which often require higher concentrations to achieve complete bactericidal effects [32]. Overall, the findings of this study demonstrate that both ZnO-NPs and thyme essential oil nanoparticles are effective antimicrobial agents against *C. jejuni*, with thyme nanoparticles showing superior efficacy under the tested conditions. These results support the growing body of evidence that nanotechnology-based antimicrobial systems represent a promising alternative to conventional chemical preservatives and antibiotics in food safety applications.

However, despite their effectiveness, further research is needed to evaluate the toxicological safety, regulatory acceptance, and long-term stability of these nanomaterials in food systems. Future studies should also explore synergistic combinations and real food matrix applications to optimize their practical use.

Conclusion

Campylobacter jejuni remains a prevalent foodborne pathogen, particularly in processed meat products. The detection of the pathogen among food handlers further highlights the critical role of hygiene practices in preventing cross-contamination.

The detection of these virulence determinants in food-derived *C. jejuni* isolates underscores the potential risk associated with contaminated food products. The presence of adhesion (*cadF*), motility (*flaA*), and toxin (*cdtB*) genes suggests that these strains possess the necessary attributes for successful colonization and disease development. Therefore, continuous monitoring of virulence gene profiles is essential for risk assessment and the development of effective control strategies in food safety systems.

Both Zinc Oxide Nanoparticles (ZnO-NPs) and thyme essential oil nanoparticles exhibited significant antimicrobial activity against *C. jejuni*. However, thyme essential oil nanoparticles showed superior efficacy, achieving complete inhibition at all tested concentrations, whereas ZnO-NPs required higher concentrations to exert a comparable effect.

These findings suggest that thyme essential oil nanoparticles represent a promising, natural, and efficient strategy for controlling *C. jejuni* in food systems. Their application could contribute to improved food safety and reduced reliance on conventional antimicrobials. Future research should focus on safety assessment, regulatory aspects, and large-scale application in real food matrices.

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References

1. Dasti JI, Tareen AM, Lugert R, Zautner AE, Gross U. *Campylobacter jejuni*: a brief overview on pathogenicity-associated factors and disease-mediating mechanisms. Int J Med Microbiol. 2010; 300(4): 205-211.

2. Feng J, Lamour G, Xue R, Mirvakliki MN, Hatzikiriakos SG, Xu J, et al. Chemical, physical and morphological properties of bacterial biofilms

affect survival of encased Campylobacter jejuni F38011 under aerobic stress. Int J Food Microbiol. 2016; 238: 172-182.

3. Kemper L, Hensel A. Campylobacter in the food chain: Epidemiology, antimicrobial resistance, and control strategies. Food Microbiology. 2023; 110: 104142.
4. Loera-Muro A, Silva-Jara J, Hernández V, León-Montoya H, Angulo C. A perspective on nanomaterials against *Campylobacter jejuni* biofilm – New control strategies. Microbial Pathogenesis. 2024; 197: 107031.
5. World Health Organization (WHO). Campylobacter. 2019.
6. Misra NN, Dixit Y, Al-Mallahi A, Bhullar MS, Upadhyay R, Martynenko A. IoT, Big Data, and Artificial Intelligence in Agriculture and Food Industry. IEEE Internet of Things Journal. 2022; 9: 6305-6324.
7. Rout SS, Pradhan KC. A review on antimicrobial nano-based edible packaging: Sustainable applications and emerging trends in food industry. Food Control. 2024; 163: 110470.
8. Almaary KS. Food-Borne Diseases and their Impact on Health. Biosciences Biotechnology Research Asia. 2023; 20: 745-755.
9. Hakeem MJ, Feng J, Nilghaz A, Ma L, Seah HC, Konkel ME, et al. Active packaging of immobilized zinc oxide nanoparticles controls *Campylobacter jejuni* in raw chicken meat. Appl Environ Microbiol. 2020; 86(22): e01195-20.
10. Ghaneem HE, Hamouda AS, Shakel M, Marouf S, Sobhy MM. The effect of probiotic and thyme oil nanoparticles on controlling colonization of *Campylobacter jejuni* in broiler chickens. IOSR Journal of Agriculture and Veterinary Science. 2024; 17: 1-9.
11. Yu Z, Zhao Y, Xie Y. Ensuring food safety by artificial intelligence-enhanced nano-sensor arrays. Adv Food Nutr Res. 2024; 111: 139-178.
12. Zafeer MF, Imran M. Antimicrobial potential of nanomaterials against foodborne pathogens: Mechanisms and applications. Food Biosci. 2024; 59: 103456.
13. Li D, Chen F, Dong Z, Jia F, Wen R, Sun C, et al. Electrospun PLA/ZnO composite films: Enhanced antibacterial properties and application in fresh chicken meat preservation. Food Packaging and Shelf Life. 2025; 49: 101536.
14. International Organization for Standardization. ISO 10272-1:2017. Microbiology of the food chain - Horizontal method for detection and enumeration of Campylobacter spp. Part 1: Detection method. ISO. 2017.
15. Ibrahim AK, Salama AM, Shemis MA, Awad AA. Fortifying human health: nano-oils and the fight against resistant bacterial food contamination. Infect Dis Res. 2025; 6(2): 10.
16. Jayari A, Jouini A, Boukhris H, Hamrouni S, Damergi C, Ahmed, SB. Essential oils from Thymus capitatus and Thymus algeriensis as antimicrobial agents to control pathogenic and spoilage bacteria in ground meat. Journal of Food Quality. 2021.
17. Windiasti G, Feng J, Ma L, Hu Y, Hakeem MJ, Amoako K, et al. Investigating the synergistic antimicrobial effect of carvacrol and zinc oxide nanoparticles against *Campylobacter jejuni.* Food Control. 2019; 96: 39-46.
18. Centers for Disease Control and Prevention. About *Campylobacter* infection. 2024.
19. Méndez-Olvera E, Verdugo-Rodríguez A, López-Vidal Y. Virulence factors of *Campylobacter jejuni* involved in adherence and invasion of host epithelial cells. Frontiers in Cellular and Infection Microbiology. 2016; 6: 54.
20. Li Z, Cai H, Xu B, Dong Q, Jia K, Lin Z, et al. Prevalence, antibiotic resistance, resistance and virulence determinants of *Campylobacter jejuni* in China: A systematic review and meta-analysis. One Health. 2025; 20: 100990.
21. Omole Z, Dorrell N, Elmi A, Nasher F, Gundogdu O, Wren BW. Pathogenicity and virulence of *Campylobacter jejuni:* What do we really know? Virulence. 2024; 15(1): 2436060.
22. Sierra-Arguello YM, Perdoncini G, Rodrigues LP, dos Santos LR, Borges KA, Furian TK, et al. Identification of pathogenic genes in *Campylobacter jejuni* isolated from broiler carcasses and broiler slaughterhouses. Sci Rep 2021; 11: 4588.
23. Tikhomirova A, McNabb E, Petterlin L, Bellamy GL, Lin KH, Santoso KA, et al. *Campylobacter jejuni* virulence factors: update on emerging issues and trends. J Biomed Sci. 2024; 31(1): 45.
24. Wanja DW, Mbindyo CM, Mbuthia PG, Bebora LC, Aboge GO. Molecular Detection of Virulence-Associated Markers in *Campylobacter coli* and *Campylobacter jejuni* Isolates From Water, Cattle, and Chicken Faecal Samples From Kajiado County, Kenya. Biomed Res Int. 2024.
25. Sharafutdinov I, Tegtmeyer N, Müsken M, Backert S. *Campylobacter jejuni* serine protease HtrA induces paracellular transmigration of microbiota across polarized intestinal epithelial cells. Biomolecules. 2022; 12(4): 521.
26. Djahra AB, Snagriaa I, Benkaddoura M, Bensmail S, Benkherarab S, Rania B, et al. Green synthesis of zinc oxide nanoparticles using Ocimum basilicum essential oil: antioxidant and antibacterial activities against pathogenic bacteria. Green Chemistry Letters and Reviews. 2025; 18: 2583874.
27. Chan YB, Aminuzzaman M, Tey LH, Win YF, Watanabe A, Djearamame S, et al. Impact of Diverse Parameters on the Physicochemical Characteristics of Green-Synthesized Zinc Oxide–Copper Oxide Nanocomposites Derived from an Aqueous Extract of Garcinia mango Stana L. Leaf. Materials. 2023; 16: 5421.
28. Pires HM, Bastos LM, da Silva EF, Fonseca BB, Sommerfeld S, Junior RJO, et al. Antimicrobial activity of essential-oil-based nanostructured lipid carriers against Campylobacter spp. Isolated from Chicken Carcasses. Pharmaceutics. 2024; 16(7): 922.
29. Pimentel LS, Sommerfeld S, Braga PF, Coleto AF, Fonseca BB, Bastos LM, et al. Antitumor activity of essential oils-based nanostructured lipid carriers on prostate cancer cells. Int J Pharm. 2024; 657: 124149.
30. Sobhy M, Elsamahy T, Abdelkarim EA, Khojah E, Cui H, Lin L. Cardamom essential oil-loaded zinc oxide nanoparticles: A sustainable antimicrobial strategy against multidrug-resistant foodborne pathogens. Microb Pathog. 2025; 205: 107661.
31. Hou T, Sana SS, Li H, Xing Y, Nanda A, Netala VR, et al. Essential oils and its antibacterial, antifungal and anti-oxidant activity applications: A review. Food Biosc. 2022; 47: 101716.
32. Ellboudy NM, Elwakil BH, Shaaban MM, Olama ZA. Cinnamon Oil-Loaded Nanoliposomes with Potent Antibacterial and Antibiofilm Activities. Molecules. 2023; 28: 4492.