

BIOSENSORS AS POWERFUL TOOLS FOR *CAMPYLOBACTER* SPP. DETECTION

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Abstract: *Campylobacter* spp. of the *Campylobacteriaceae* family are spiral-shaped, Gram-negative, zoonotic pathogens. These microaerophilic, thermophilic bacteria flourish at temperatures of 37-42 °C. *Campylobacter* spp. are known pathogens of animals (livestock, wild, and companion animals) and humans. They are also a major foodborne pathogen. Traditional culture-based detection of *Campylobacter* spp. is labor-intensive, requires 5 to 7 days for confirmation, and is often compromised by overgrowth of competing bacteria. While molecular methods are sensitive, they require specialized instruments and well-trained personnel, limiting their routine use for rapid on-site detection. Analytical biosensors have emerged as powerful tools for the real-time diagnosis of infectious diseases. Biosensors such as mass-sensitive, amperometric, total internal reflection fluorescence (TIRF), impedimetric, surface-plasmon resonance (SPR), conductometric, fluorescence resonance energy transfer (FRET), and diffractive optics have been developed for bacterial identification. Depending on the sensing platform, reported limits of detection range from a single bacterial cell per sample to about 10⁴ CFU/ml, with several biosensors providing results within minutes to a few hours, highlighting their potential for rapid food safety monitoring and clinical diagnosis. This review elaborates on various types of biosensors for the diagnosis of *Campylobacter* spp. and related species.

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Keywords: *Campylobacter* spp., biosensors, detection, amperometric, impedimetric, conductometric

1. Introduction

Zoonotic *Campylobacter* spp. are globally associated with bacterial diarrhea (Njoga *et al.* 2025). The Gram-negative *Campylobacter* species are microaerophilic, curved or spiral-shaped bacteria that possess a single, polar, unsheathed flagellum at one or both ends. *C. jejuni* is a common foodborne pathogen that causes infectious diarrhea worldwide (Abul-

reesh *et al.* 2017). In humans, infection predominantly occurs through handling and ingestion of contaminated poultry meat (uncooked or raw), tap water, and raw milk. Infection may present with abdominal pain, vomiting, mild, self-limiting gastroenteritis with fever (1-3 days), and bloody, watery diarrhea (3-7 days) (Kim *et al.* 2021; Graham *et al.* 2024). *Campylobacter*-associated infections may lead to Guillain-Barre syndrome (GBS), a rare, life-threatening autoimmune condition that fre-

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quently results in long-term sequelae such as irritable bowel syndrome and reactive arthritis (Abulreesh *et al.* 2017). Therefore, *Campylobacter* detection is crucial for food safety and public health. Traditional culture-based methods are considered the “gold standard” for *Campylobacter* spp. detection and diagnosis. However, these techniques are time-consuming (5-7 days), and in heavily contaminated samples, overgrowth of competing microflora can produce false-negative results by preventing *Campylobacter* spp. from reaching detectable levels (Abulreesh *et al.* 2005). *C. jejuni* can cause serious outbreaks, particularly in older adults and infants. Therefore, rapid detection is important for curbing the spread of the pathogen and preventing a detrimental outbreak (Huang *et al.* 2021). Multiple *Campylobacter* spp. detection methods are available and are classified as conventional cultural methods [plating/culturing, microscopic and biochemical confirmation, and enumeration] and modern immunological and molecular methods [testing kits and PCR/hybridization] (Neyaz *et al.* 2024). However, these

techniques can be expensive and time-consuming, with laborious sample preparation, and may generate incomplete or misleading data. In this regard, biosensors may offer significant advantages over traditional approaches (Oyarzabal and Battie, 2012). To our knowledge, the use of biosensors for *Campylobacter* spp. detection is limited and scattered. Therefore, this review provides an overview of different types of biosensors to improve understanding and detection of *Campylobacter* species.

2. Classification of Biosensors

Biosensors are analytical instruments that integrate a biological recognition component with a signal transducer to identify a specific target (Ali *et al.* 2017). Biosensors for *Campylobacter* spp. detection can be categorized as electrochemical, optical, or mass-sensitive devices based on the transduction mechanism employed (Yang *et al.* 2013; Yasmin *et al.* 2016). Figure 1 summarizes the basic concept of biosensor operation.

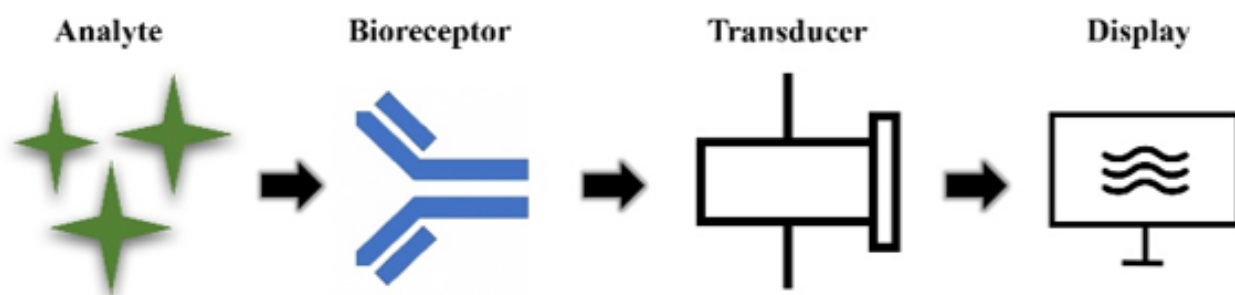


Fig. 1: General working principle of a biosensor showing the interaction among the target analyte, the biological recognition element, the transducer, and the signal processing unit.

2.1 Electrochemical biosensors

Electrochemical biosensors are extensively researched platforms for detecting *Campylobacter* spp. because of their rapid analysis, high sensitivity, portability, and compatibility with diverse food matrices (Yang *et al.* 2013; Aleksic and Kapetanovic 2013; Sumitha and Xavier 2023). These biosensors convert biological recognition events into quantifiable electrical signals (Fig. 2) and can be categorized as amperometric, impedimetric, and conductometric systems. Numerous electrochemical biosensors have been developed for the identification of *Campylobacter* spp. in food, environmental, and clinical specimens.

2.1.1 Amperometric biosensors

Amperometric biosensors measure current changes generated during biological recognition events and have been widely used for pathogen detection (Fig. 3). A biosensor design used electron transfer through a bilayer lipid membrane (BLM) to detect *Campylobacter* spp. It involved immersing a stainless-steel (SS) electrode in an egg phosphatidylcholine-based squalene-decane solution (1:1) to form a BLM. Soaking the electrode for 5 hours immobilized *Campylobacter* spp.-specific antibodies. The dielectric BLM blocked electron transfer to the electrode. However, antibody conformational perturbation upon bacterial binding opened a channel

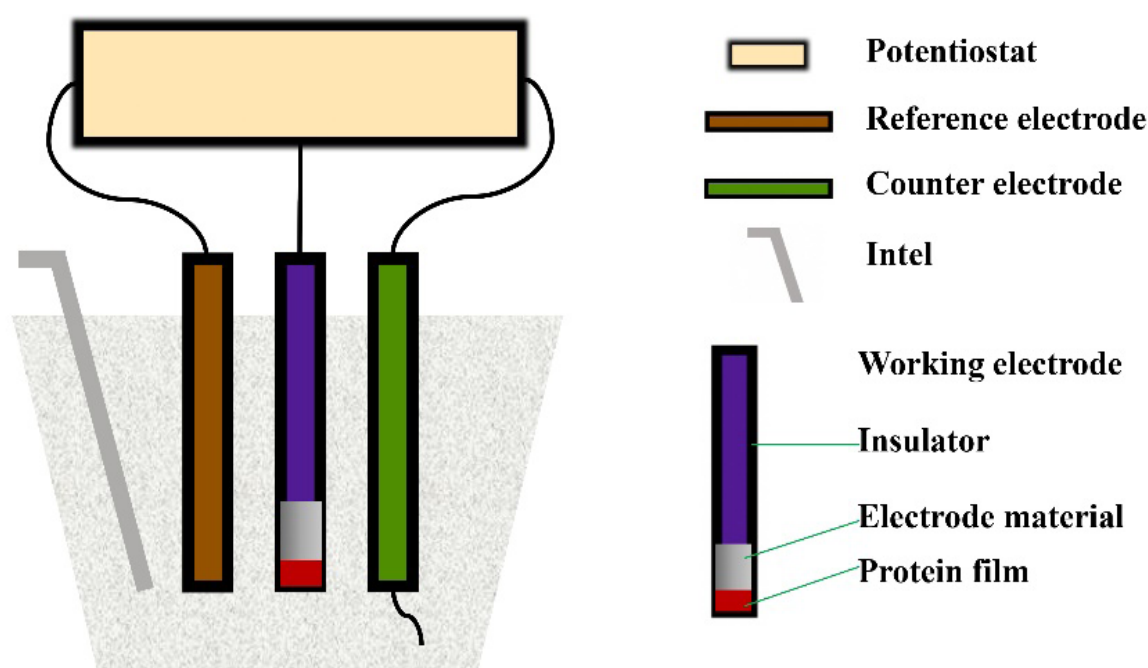


Fig. 2: Basic structure of an electrochemical biosensor cell, illustrating the working, reference, and counter electrodes that convert biological recognition events into measurable electrical signals.

for ion permeation through the BLM, yielding a current peak in the amperometric biosensor. The current peaks were of the same size irrespective of the cell concentration, indicating channel opening or closing, whereas the concentration determined the current peak's width. The current peaks corresponded to a flow of approximately 10^{10} ions/s, suggesting an LOD of one cell/sample (Ivnitski *et al.* 2000).

Another design used magnetic beads to confine the bacteria. Initially, streptavidin was used to modify the beads, followed by immobilization of biotinylated rabbit anti-*C. jejuni* via an avidin-biotin interaction and phosphatase labeling. The bead-bacteria conjugates were formed by mixing and shaking the beads with bacteria for an hour. The immunomagnetic separation method compared eight bead types of varying sizes and modifications to achieve optimal cell capture. After removing the supernatant, the conjugates were incubated with phenyl phosphate for 1 hour to produce phenol. A tyrosinase-modified carbon-paste electrode detected the phenol, and the current signal was recorded. This design was used to measure *C. jejuni* in ground turkey meat, washing water, chicken carcass, and PBS. The study revealed similar bacterial results in the poultry samples and PBS. A logarithmic concentration was used for linear fitting. The linear detection

range remained 10^2 - 10^7 CFU/ml, with a fitting variation (R^2) of 0.94, whereas the limit of detection was noted as 2×10^4 CFU/ml (Che *et al.* 2001). Viswanathan *et al.* (2013) employed an antibody-bacteria-antibody strategy. Nanocrystals were used to design amperometric biosensors for detecting *Campylobacter* spp., including *C. jejuni*. Carboxylic acid-functionalized multi-walled carbon nanotubes (MWCNT) were used to modify a screen-printed electrode (SPE), followed by immobilization of *Campylobacter* spp.-specific antibodies. They observed a limit of detection (LOD) range of 1×10^3 to 5×10^5 CFU/ml, whereas 4×10^2 CFU/ml was noted in a sigmoidal current response.

Amperometric biosensors have demonstrated superior analytical performance for detecting *Campylobacter* spp., with reported LODs ranging from a single *Campylobacter* cell per sample to 2×10^4 CFU/ml, depending on the sensing technique. These biosensors have been effectively evaluated in phosphate-buffered saline (PBS), poultry rinse water, raw poultry meat, ground turkey meat, and several other food matrices. Their rapid response, portability, and compatibility with complex food samples make amperometric biosensors among the most promising electrochemical platforms for routine *Campylobacter* spp. surveillance.

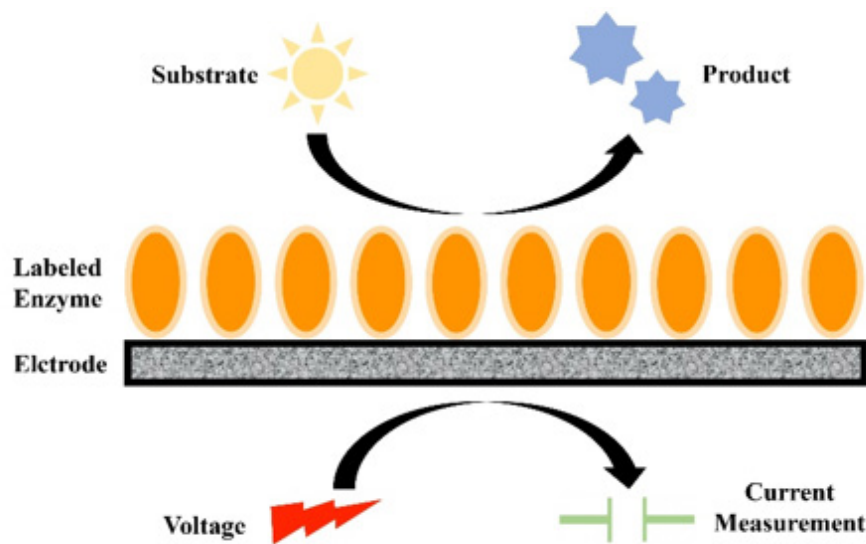


Fig. 3: Working principle of an amperometric biosensor. The biological interaction at the sensing surface produces an oxidation or reduction current proportional to the concentration of the target analyte.

2.1.2 Impedimetric biosensors

Impedimetric biosensors detect changes in electrical impedance caused by target binding and have shown promise for rapid *detection of Campylobacter* spp. (Fig. 4). Several impedance-based biosensors have been reported in recent years. Fe₃O₄ nanoparticles were used to develop an impedimetric biosensor for detecting *C. jejuni* in patient stool, with a glassy carbon electrode serving as the working electrode. The electrode was coated with an O-Carboxymethyl-

chitosan (OCMCS)-modified Fe₃O₄ nanoparticle suspension, followed by immobilization via immersion in the anti-*Campylobacter jejuni* monoclonal antibody 2D12. Non-specific binding was blocked by applying BSA. Bacteria-containing PBS (pH 7) buffer was used to incubate the electrodes for 40 min at 37.5 °C, and the limit of detection was reported as 10³ CFU/ml (Huang *et al.* 2010). Impedimetric biosensors offer several advantages over amperometric biosensors, including label-free detection, streamlined assay design, and reduced reagent

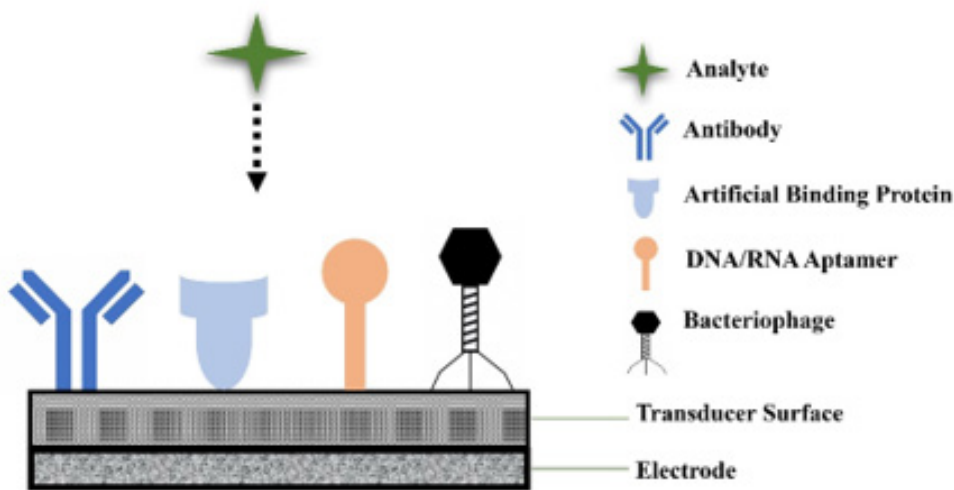


Fig. 4: Schematic representation of an impedimetric biosensor for bacterial detection, showing immobilized bioreceptors on the electrode surface and the resulting change in charge-transfer resistance upon target binding.

use. They directly detect changes in electrical impedance caused by bacterial adhesion, without requiring electroactive labels or enzyme substrates. However, impedimetric sensors are typically more susceptible to electrode fouling, non-specific adsorption, and fluctuations arising from complex food matrices, which can compromise reproducibility. Despite these constraints, their rapid response and simple sensor architecture make them appealing options for point-of-care and food safety applications for *Campylobacter* spp. detection.

2.1.3 Conductometric biosensors

Conductometric biosensors measure changes in electrical conductivity caused by microbial growth or metabolic activity. Despite fewer conductometric platforms reported for *Campylobacter* spp. detection than for amperometric or impedimetric systems, they have shown promise for monitoring bacterial growth and viability in culture media.

Monitoring changes in the medium's conductance could reveal *Campylobacter* growth (Cappelier *et al.* 2000). A capacitance-based detection technique has been reported to monitor *C. jejuni* growth, thereby facilitating analysis of injured *C. jejuni* cells in an optimal broth medium. This method involved monitoring bacterial metabolism in addition to analyzing capacitance changes in the solution. The detection times (DTs) at minimum capacitance were linked to the initial cell concentrations, which were 17, 21, 25, 29, and 35 h for 10^4 , 10^3 , 10^2 , 10, and 1 CFU/ml, respectively (Line and Pearson 2003).

Although only a relatively small number of conductimetric biosensors have been specifically developed for *Campylobacter* spp. (Wang *et al.* 2023; Vizzini *et al.* 2026), recent advances in electrochemical sensing, microfluidic platforms, and portable biosensor technologies offer renewed possibilities for conductimetric detection (Wang *et al.* 2023; Madadelahi *et al.* 2025). Improvements in electrode materials, nanostructured conductive polymers, and integrated lab-on-a-chip systems are expected to increase sensitivity, reduce detection time, and enable real-time monitoring of *Campylobacter* spp. in food processing environments (Vizzini *et al.* 2026). Future studies should aim to transfer these technological advances into conductimetric platforms optimized for *Campylobacter* spp. detection.

2.2 Optical biosensors

Optical biosensors provide rapid, highly sensitive detection by measuring optical signal changes generated by target recognition and include SPR, TIRE, diffractive optics, and FRET-based systems (Yang *et al.* 2013; Singh *et al.* 2023).

2.2.1 Surface plasmon resonance (SPR) biosensors

SPR biosensors enable real-time, label-free detection based on changes in refractive index at the sensor surface (Fig. 5) and have been successfully applied to *Campylobacter* spp. detection (Poltronieri *et al.* 2014; Al Mahmud *et al.* 2023). The SpreetaTM dual-channel SPR sensor is a commercial SPR biosensor for the real-time detection of *Campylobacter* species. It involves immobilizing the rabbit polyclonal IgG antibody on the sensor surface. In a study, this sensor efficiently detected *C. jejuni* (10^2 to 10^9 CFU/ml) in meat rinse and pure culture samples (Wang and Salazar 2015). Yang *et al.* (2013) reviewed the development of an eight-channel SPR sensor for *C. jejuni* detection in apple juice (pH 3.7 and 7.4) and buffer (pH 7.4). Glass chips served as substrates in this biosensor, with gold (Au) and chromium (Cr) deposited by vacuum evaporation. A self-assembled monolayer (SAM) of Biotinylated alkanethiol: Oligo (ethylene glycol) (BAT: OEG) was used to functionalize the sensor. Then, biotinylated polyclonal rabbit antibody (PAb) and streptavidin were added. All eight channels were functionalized with different antibodies, enabling simultaneous multi-analyte detection with a detection limit of 1.1×10^5 CFU/ml in apple juice and PBS. Moreover, SPR biosensors can be optimized to investigate bacterial interactions for the development of antimicrobials against pathogenic bacteria. Masdor *et al.* (2014) developed an SPR biosensor platform for *C. jejuni* detection through in-house cultivation of *C. jejuni* strains. A covalent attachment technique was used to raise polyclonal antibodies against *C. jejuni*, which were then used to functionalize SPR sensor chips, followed by induction of gold (Au) chips for direct *C. jejuni* detection within a limit of 8×10^6 CFU/ml. The SPR-based sandwich biosensor was also compared with ELISA and proved to be an excellent alternative for *C. jejuni* detection.

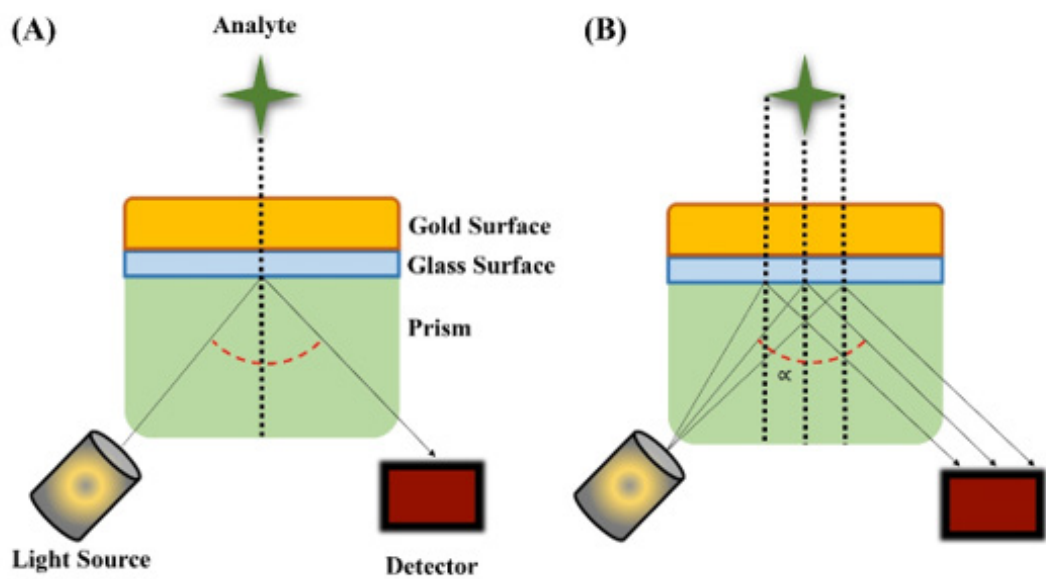


Fig. 5: Surface plasmon resonance (SPR)-based biosensor. (A) Changes in the angle of refracted light after analyte binding. (B) Generation of an evanescent field at the thin gold surface, enabling label-free, real-time detection.

2.2.2 Total internal reflection fluorescence (TIRF) (Array biosensor)

TIRF biosensors employ fluorescence-based detection and offer high sensitivity for pathogen identification in complex samples (Fig. 6) (Colson *et al.* 2023). Gnanaprakasa *et al.* (2011) conducted a sandwich immunoassay to test a sensor’s capability to detect *C. coli* and *C. jejuni* in buffer and in various foods, including

lettuce leaf, turkey, milk, and carcass wash. EZ-link biotin-LC-HNS was used to biotinylate monoclonal rabbit antibodies against *C. jejuni*, and a Cy5 bifunctional dye was used for labeling. Poly(dimethyl) siloxane (PDMS) flow cells were used to pattern these antibodies on the glass waveguide. The limit of detection for *C. jejuni* was 5×10^2 , 4×10^3 , 5×10^2 , 5×10^2 , and 2×10^3 CFU/ml in ground turkey ham, ground turkey sausage, milk, and yogurt, respectively.

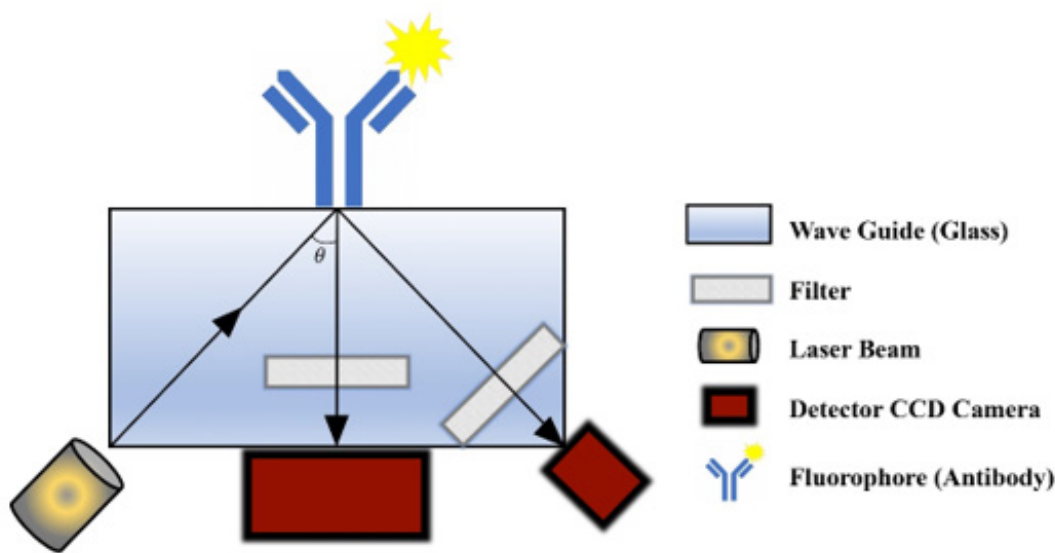


Fig. 6: Total internal reflection fluorescence (TIRF) array biosensor system showing the optical, fluidic, waveguide, and detection components used for pathogen detection by fluorescence.

2.2.3 Diffractive optics

Diffractive optical biosensors detect target binding through changes in diffraction patterns (Fig. 7) (McGovern *et al.* 2023) and have been applied to the identification of *Campylobacter* spp. Gnanaprakasa *et al.* (2011) employed the dotLab system to detect unique DNA segments of *C. jejuni* and compared the results with those from the Spreeta SPR biosensor. The results revealed that unique DNA segments of the *hippuricase* gene were expressed only in *C. jejuni*, demonstrating specificity for this pathogen. The LOD remained at 5 nM for dotLab and 2.5 nM for SPR in PBST buffer (PBS & Tween). In another investigation, a novel bi-

osensor-based detection method, BARDOT (Bacterial Rapid Detection using Optical scattering Technology), was developed for high-throughput screening of *Campylobacter* colonies on an agar plate without disruption. During the study, principal component analysis (PCA) and image pattern characterization were performed on 6909 bacterial colonies. The data demonstrated 85% detection accuracy and showed significantly different light-scattering patterns for *C. coli* and *C. jejuni* compared with *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli* O157:H7. The BARDOT biosensor is recommended for detection of *Campylobacter* spp. in naturally contaminated fresh chicken meat and spiked ground chicken (He *et al.* 2014).

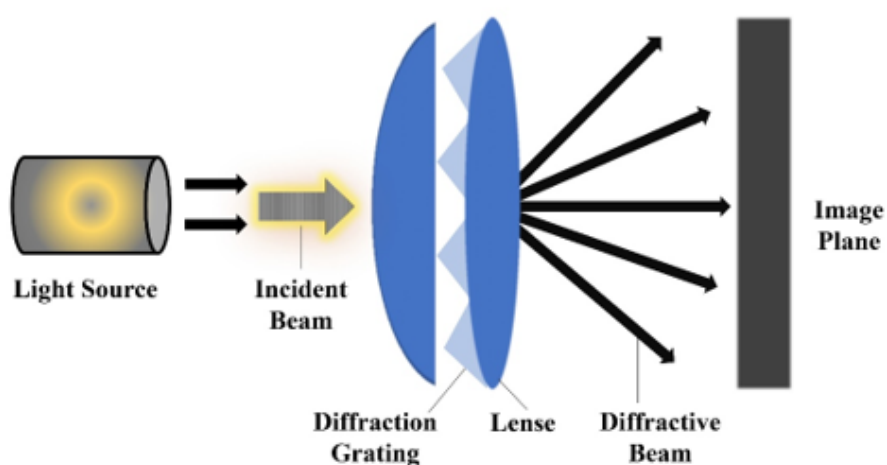


Fig. 7: Principle of a diffractive-optic biosensor. Binding of the target analyte to immobilized capture molecules increases diffraction intensity, enabling label-free detection.

2.2.4 Fluorescence resonance energy transfer (FRET)

FRET biosensors use energy transfer between fluorescent molecules to detect specific nucleic acid targets (Fig. 8) and have been explored for *Campylobacter* spp. DNA detection. Darbha *et al.* (2008) developed a gold nanoparticle-based miniaturized FRET probe for *Campylobacter* DNA screening. They reported that nanoparticle-based FRET can monitor biological events over a 10 nm distance limit. The reduction of H₂AuCl₄ was used to synthesize gold nanoparticles for the probe, whereas homocysteine (Hcys) and mercapto propionic acid (MPA) were used for surface modification. A fluorescent staining dye (Rhodamine B) aqueous solution tagged with *Campylobacter*-associated single-stranded DNA (ss-DNA, 5'GTAAGTTC-

CATTCTCTTTGG3') was used to immerse the gold nanoparticles. This biosensor had a linear detection range of 0.8 – 7x10⁴ nM.

2.3 Mass-sensitive biosensors

Mass-sensitive biosensors detect changes in sensor mass after target binding (Fig. 9) (Sharma *et al.* 2013; Singh *et al.* 2024) and have been investigated for *Campylobacter* detection using quartz crystal microbalance (QCM)-based platforms. A lectin-based QCM biosensor has been successfully used for *C. jejuni* detection. Lectins are non-immune glycoproteins from animals and plants. They specifically bind various carbohydrates and offer greater stability than antibodies (Safina *et al.* 2008; Yakovleva *et al.* 2011). Masdor *et al.* (2016)

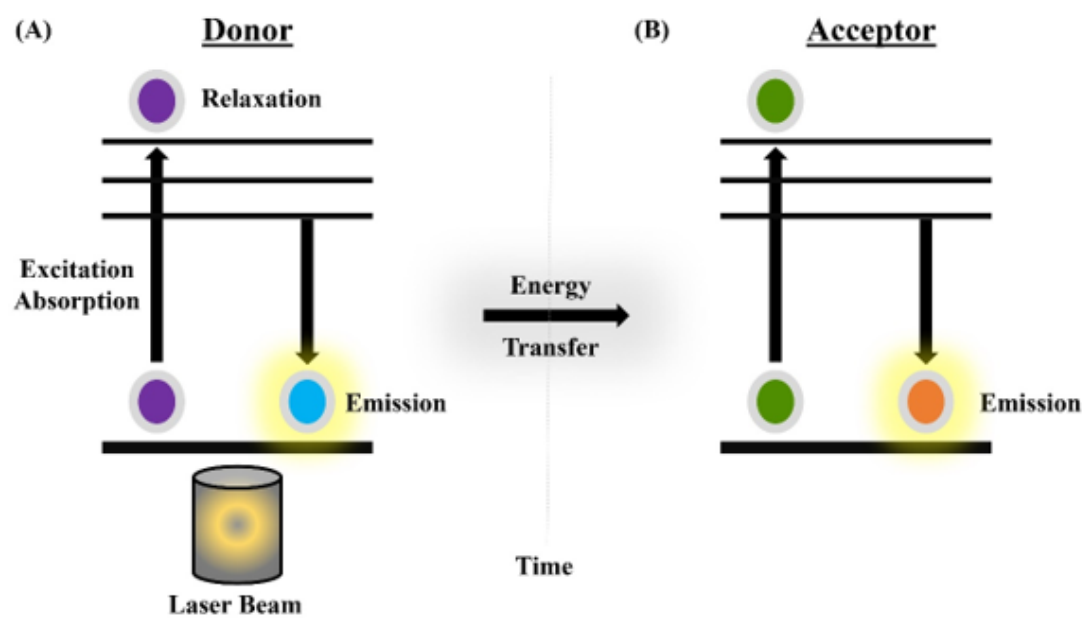


Fig. 8: Fluorescence resonance energy transfer (FRET) event. (A) Excitation of the donor molecule by a laser beam. (B) Donor and acceptor photon-emission signals over time. (C) Use of donor-acceptor energy transfer to estimate intramolecular distance.

developed a QCM-based immunosensor for *C. jejuni* detection. Commercial mouse monoclonal and rabbit polyclonal antibodies were used to construct direct sandwich assays with gold nanoparticles (AuNPs) for *C. jejuni* detection. A limit of detection (LOD) of 150

CFU/mL was observed in solution. The QCM sensor exhibited excellent specificity and sensitivity for *Campylobacter* spp. detection. The data also revealed low cross-reactivity with *Listeria monocytogenes* (3%), *Salmonella* Typhimurium (7%), and *Escherichia coli* (0).

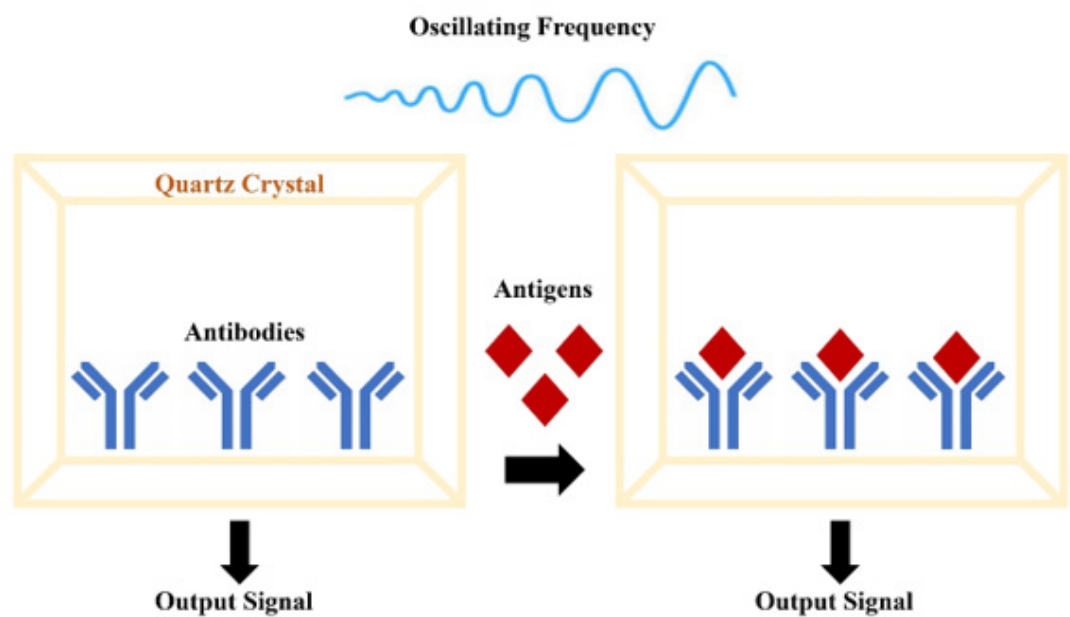


Fig. 9: Quartz crystal microbalance (QCM)-based mass-sensitive biosensor. Antibodies immobilized on the crystal surface specifically capture target antigens, increasing sensor mass and shifting the oscillation frequency, which is converted into an electrical signal.

Table 1. Comparative summary of biosensor platforms reported for *Campylobacter* spp. detection

Biosensor platform	Target analyte / recognition element	LOD	Sample type	Advantages	Disadvantages / limitations	References
Amperometric biosensor	<i>Campylobacter</i> spp. cells; antibodies immobilized on bilayer lipid membrane or magnetic beads	One cell/sample to 2×10^4 CFU/ml; reported ranges up to 10^7 CFU/ml	PBS, ground turkey meat, washing water, chicken carcass rinse	Rapid, portable, compatible with food matrices, low-cost transducers	Signal may depend on antibody quality, sample preparation, and matrix effects	Ivnitski <i>et al.</i> 2000; Che <i>et al.</i> 2001; Viswanathan <i>et al.</i> 2013
Impedimetric biosensor	<i>C. jejuni</i> cells; monoclonal anti- <i>C. jejuni</i> antibody on Fe ₃ O ₄ nanoparticle-modified electrode	10^3 CFU/ml	Patient stool / PBS buffer	Label-free, relatively rapid, suitable for miniaturization	Electrode fouling and non-specific binding may affect reproducibility	Huang <i>et al.</i> 2010
Conductometric / capacitance-based biosensor	<i>C. jejuni</i> growth/metabolism; conductance or capacitance change	Detection times reported for 1 to 10^4 CFU/ml	Optimal broth medium / injured cells	Useful for monitoring viable cells and metabolic activity	Longer detection time than direct molecular biosensors; requires growth conditions	Cappelletti <i>et al.</i> 2000; Line and Pearson, 2003
SPR biosensor	<i>C. jejuni</i> cells; polyclonal or monoclonal antibodies on gold sensor chip	1.1×10^5 CFU/ml to 8×10^6 CFU/ml; some systems tested 10^2 to 10^9 CFU/ml	Pure culture, meat rinse, apple juice, PBS	Label-free, real-time, multiplex channel formats possible	Higher instrumentation cost; surface regeneration and matrix interference need optimization	Yang <i>et al.</i> 2013; Masdor <i>et al.</i> 2014; Wang and Salazar, 2015
TIRF / array biosensor	<i>C. jejuni</i> and <i>C. coli</i> ; fluorescent antibody-based sandwich immunoassay	5×10^2 to 4×10^3 CFU/ml depending on matrix	Ground turkey, milk, yogurt, carcass wash	High sensitivity, real-time fluorescence detection, suitable for multiplex arrays	Requires fluorescent labels, optical alignment, and specialized instrumentation	Gnanaprakasa <i>et al.</i> 2011
Diffraction optics / BARDOT	<i>C. jejuni</i> DNA or colony light-scattering pattern	5 nM DNA for dotLab; BARDOT classification accuracy around 85%	PBST buffer, agar colonies, fresh and spiked chicken samples	Label-free options, non-destructive colony screening, high-throughput potential	Requires pattern analysis and validation with naturally contaminated samples	Gnanaprakasa <i>et al.</i> 2011; He <i>et al.</i> 2014
FRET biosensor	<i>Campylobacter</i> DNA; fluorescent ssDNA probe and gold nanoparticles	0.8 to 7×10^4 nM	Laboratory DNA samples	High molecular specificity and useful for nucleic acid detection	Requires labeled probes and controlled assay conditions	Darbha <i>et al.</i> 2008
Mass-sensitive / QCM biosensor	<i>C. jejuni</i> cells; lectins or antibody-based capture molecules on quartz crystal	Not consistently reported; applied for <i>C. jejuni</i> detection in experimental systems	Bacterial suspensions / assay buffer	Label-free, real-time mass-change monitoring	Surface immobilization, cross-reactivity, and matrix robustness require optimization	Safina <i>et al.</i> 2008; Yakovleva <i>et al.</i> 2011; Masdor <i>et al.</i> 2016

3. Challenges

C. jejuni is a global foodborne human pathogen. Traditionally, cultural and molecular methods are used to analyze food, blood, urine, and saliva samples for pathogen detection. The fastidious nature of *C. jejuni* complicates the development of optimal methods and culture media, as it requires capnophilic (3 to 5% CO₂) and microaerophilic (5% O₂) conditions for growth. Sensitivity to low temperatures, desiccation, ambient oxygen, and antibiotic resistance are additional constraints in developing optimal media (Neyaz *et al.* 2024). Differentiation of *Campylobacter* species by conventional techniques is another limitation, as they exhibit nearly identical biochemical characteristics. Bacteria can enter a viable but non-culturable (VBNC) state under unfavorable conditions (Abulreesh *et al.* 2006). Moreover, cultural techniques have limited specificity and sensitivity and require trained personnel and specialized equipment (Neyaz *et al.* 2024). Therefore, these methods cannot perform real-time pathogen detection. Immunological methods (ELISAs) are often employed to detect specific surface epitopes. The need for specialized equipment and technical staff makes these methods time-consuming and costly (Silva *et al.* 2011; Oyarzabal and Battie 2012). Molecular techniques (PCR amplification) offer relatively rapid *Campylobacter* identification without essentially requiring bacterial culture. However, PCR-based approaches require genetic probes that match the target sequence. Mismatched pairing can yield false positives, and genetically mutated strains may also escape detection. Conventional PCR also lacks quantification capability. By contrast, rapid real-time PCR analysis can be accomplished within hours, but it requires specific reagents and equipment, which raises the cost.

4. Future perspective

Rapid bacterial identification is critical for clinical diagnosis, treatment, and outcomes. Point-of-care screening could yield immediate results, enabling appropriate precautionary measures and barrier nursing to reduce cross-infection risks. Rapid and accurate identification of food-borne pathogens in contaminated products is essential to prevent further disease. Therefore, sensitive, rapid, and cost-effective methods for detecting pathogens are in high demand for point-of-care testing (POCT) and field use. Biosensor innovation has addressed this issue to some extent. Multiple types of biosensors have been developed and can be applied in the laboratory, in the field, or at the point of care. However, biosensor development faces lim-

itations, including reliance on synthetic cell-surface receptors and biological agents (enzymes, antibodies, and nucleic acids) (Ahmed *et al.* 2014; Vigneshvar *et al.* 2016; Zeng *et al.* 2016).

Antibodies are common bio-receptors in biosensor research. Their purification, production, and stability in biosensor design are challenging because of short shelf life and a gradual decline in binding efficiency. Recent advancements include the development of protein adhirons and mimetic antibodies, which are smaller and can be easily mass-produced and customized in bacterial systems. Challenges include (i) difficulties in achieving sensitivity and specificity in complex samples (food, blood, and feces) and (ii) difficulties in reducing cost and size for SPR, cantilever-based, and QCM sensors. Therefore, novel manufacturing processes should be adopted to improve biosensor reliability. Currently, almost two hundred companies work on bioelectronics and biosensor systems for blood glucose monitoring. Therefore, the efforts of academicians, researchers, and industries should be synchronized to commercialize laboratory-based biosensors. Selecting reproducible, cost-effective, and stable base materials is the first important step toward commercial biosensors. A broad range of base materials has been investigated; however, the individual compatibility of sensor systems should be carefully assessed. Single-chip multiplexing offers a broad range of simultaneous detection that can lower detection time and cost. These advancements require large-scale optimization, which may face funding limitations (Ahmed *et al.* 2014; Vigneshvar *et al.* 2016; Zeng *et al.* 2016).

Recent advances in biosensor technology are enabling rapid detection of *Campylobacter* spp. The combination of artificial intelligence (AI), CRISPR-based diagnostics, and lab-on-a-chip (LOC) technologies is expected to improve the sensitivity and functionality of biosensor platforms. AI can aid in interpreting complex sensor data and enable rapid analysis of food and environmental specimens, while CRISPR-Cas technology provides precise detection of *Campylobacter* spp. through sequence-specific nucleic acid identification. Furthermore, LOC devices integrated with electrochemical or optical biosensors offer compact, portable platforms that enable multiplex detection using minimal sample volumes. As these technologies advance, they are expected to facilitate expedited, precise, and field-deployable detection of *Campylobacter* spp., thereby enhancing food safety monitoring and public health surveillance (Huang *et al.* 2021; Colson *et al.* 2023; Wang *et al.* 2023; Madadelahi *et al.* 2025).

5. Conclusion

Biosensors demonstrate significant potential for rapid detection and identification of *Campylobacter* spp. and offer distinct advantages over traditional detection and identification approaches, particularly in detection speed and sensitivity. Despite the advancements achieved in the last 20 years, additional efforts are required to enhance sensor resilience, streamline their use with complex specimens, and enable routine use beyond laboratory settings. As technological advancements persist, biosensors are expected to assume a more significant role in food safety monitoring and the early detection of *Campylobacter* spp., thereby enhancing public health protection.

Authors' contributions

Conceptualization: JAK, Writing first draft: JAK, FMH, IA, LAN, KE, Resources: LAN, KE, HHA, Visualization: LAN, HHA, Writing final draft and editing: HHA.

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Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations, which might negatively affect the contents of this publication and/or claim authorship rights to this publication.



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