Check for updates

Advanced Materials Interfaces

ADVANCED MATERIALS INTERFACES Open Access

www.advmatinterfaces.de

REVIEW OPEN ACCESS

Non-Functionalized Graphene as an Electrical Sensing Surface for Bacterial Detection

Jazmin Berthe[1,2] | Sara Giancaterino[3] | Luciana Castillo[1,2] | Cristiana Boi[3,4] | Silvia Barbosa[1,2]

[1]Planta Piloto de Ingeniería Química, PLAPIQUI (UNS-CONICET), Bahía Blanca, Argentina | [2]Departamento De Ingeniería Química, Universidad Nacional del Sur, Bahía Blanca, Argentina | [3]Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Alma Mater Studiorum, University of Bologna, Bologna, Italy | [4]Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, North Carolina, USA

Correspondence: Cristiana Boi (cristiana.boi@unibo.it)

Received: 20 August 2025 | **Revised:** 24 November 2025 | **Accepted:** 4 December 2025

Keywords: bacteria | graphene | non-functionalization | sensors

ABSTRACT

Early detection of bacteria in food products is crucial for protecting human health and reducing economic losses. Although conventional methods, such as culture-based techniques, nucleic acid sequence-based detection, and immunoassays, are generally accurate, they are often time-consuming, labor-intensive, and require specialized equipment. In response to these limitations, sensing technologies emerge as simple, rapid, and cost-effective alternatives. Among these technologies, graphene gains significant attention due to its unique electrical properties and biocompatibility, making it a promising material for bacterial detection. While most efforts focus on functionalizing sensors for specific targets, recent studies demonstrate that non-functionalized graphene can effectively detect bacteria, enabling simpler and more affordable sensor design. This review provides a comprehensive analysis of non-functionalized electrical graphene-based bacterial sensors developed thus far. It evaluates and discusses the influence of graphene properties, bacterial activity, sensor design, and operational conditions on sensor performance. Additionally, the review emphasizes the need for further research to improve the reproducibility and scalability of reliable sensors and to develop sensitive, selective, and physiochemically stable devices.

1 | Introduction

The discovery of graphene in 2004, as a result of graphite exfoliation, marked a milestone in the era of nanotechnology by demonstrating the possibility of stably isolating a 2D crystalline material [1]. Graphene is flexible, has high mechanical strength, a large surface area, excellent electrical and thermal conductivity [2, 3]. In addition, it has been demonstrated to be compatible with human cells, biomolecules, and bacteria [4]. These properties have led graphene to be widely studied for several applications such as the construction of electronic devices [5, 6], energy storage [7, 8], biomedical applications [9], and sensor development [10, 11].

In the past decades, sensing technology has become increasingly important for its versatile applications both for the academic and industrial fields. It allows non-invasive and rapid measurements, can be portable and miniaturizable, and does not require complex equipment or specialized operators [12]. These characteristics are of particular interest for foodborne diseases prevention and food quality monitoring. Despite technology breakthroughs and awareness-raising efforts in society, foodborne diseases still continue to be a global public health and economic drawback [13]. Pathogenic bacteria like *Escherichia coli* (*E. coli*), *Salmonella*, and *Listeria monocytogenes*, among many other species, are the primary foodborne disease-causing agents [14]. These microorganisms pose a threat not only because of their pathogenicity,

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). *Advanced Materials Interfaces* published by Wiley-VCH GmbH

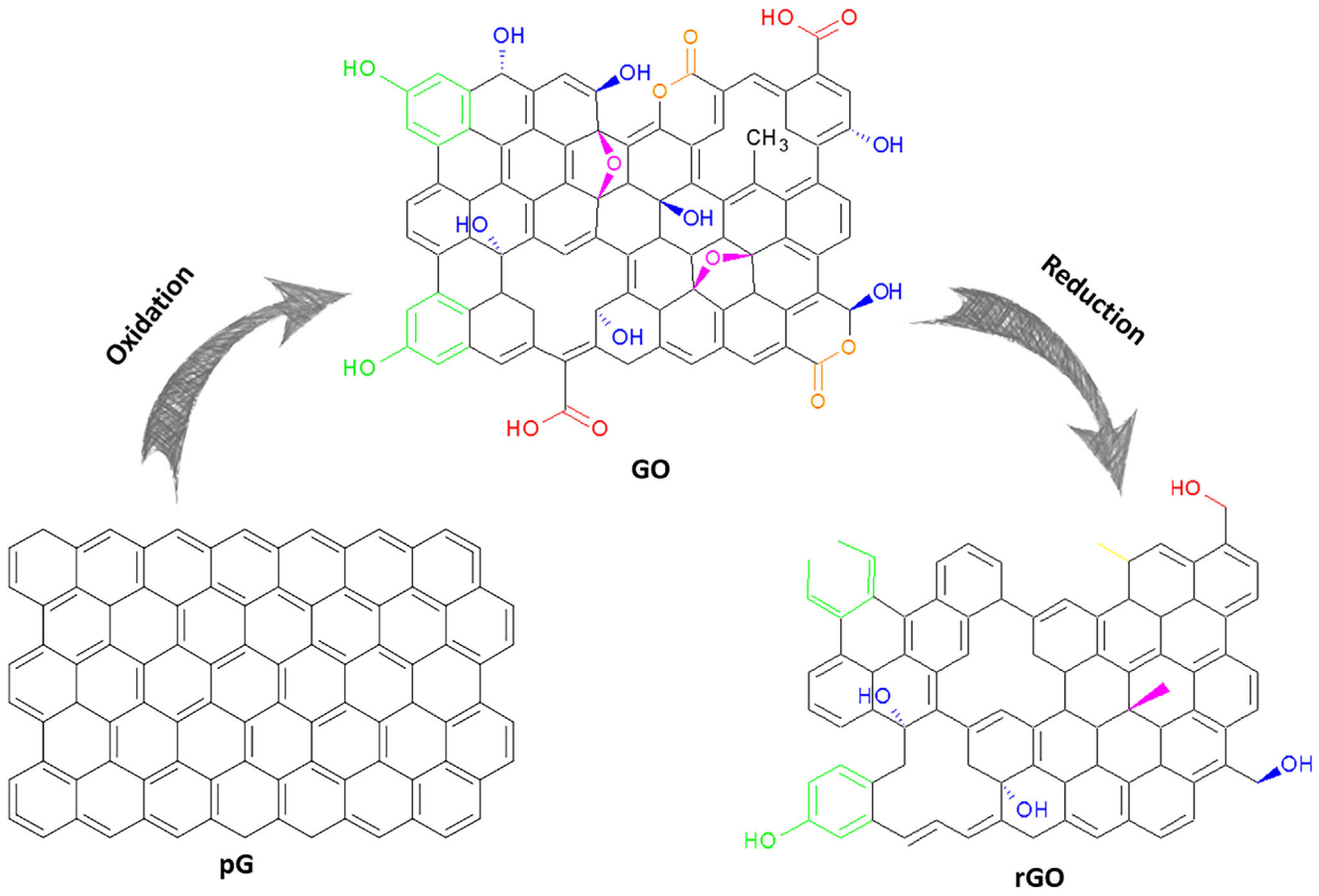

FIGURE 1 | Molecular structures of pristine graphene (pG), graphene oxide (GO), and reduced graphene oxide (rGO).

but also because they can colonize and form biofilms on the environment, making them more resistant and difficult to detect [15]. A promising approach to mitigate the preceding problem is the use of sensors to detect bacterial cells and colonies [16].

Graphene is very attractive for the development of sensors capable of detecting the presence of bacteria in food, due to the aforementioned properties, such as excellent electrical conductivity, mechanical flexibility, biocompatibility, and easy customization [17]. Graphene-based sensors often use optical, electrical, or electrochemical transduction mechanisms [18]. Particularly, electrical transduction mechanisms are widely used in bacterial sensors because they offer simplicity in design, ease of mass production, and the ability to capture and amplify signals [19]. In these sensors special emphasis has been placed, so far, on the use of graphene functionalized with biomolecules that act as bacterial receptors to obtain greater sensitivity and specificity [20, 21]. However, recent scientific developments, such as the wearable electrical sensor reported by Wibowo et al. [22], have demonstrated that non-functionalized graphene-based sensors can effectively detect and quantify bacterial presence. Furthermore, Pandit et al. [23] developed a non-functionalized graphene sensor that can differentiate between two bacterial species. This highlights the intrinsic selectivity of graphene toward biological systems. These advancements not only emphasize the potential of graphene as an active material for bacterial detection and suggest that its unique physicochemical properties can be used to address one of the most critical challenges of non-functionalized sensors: distinguishing between bacterial species or strains. These findings encourage further exploration of strategies for developing simpler, more affordable, and scalable non-functionalized graphene sensing devices.

This review focuses on a description and discussion of the state of the art in the development and operation of non-functionalized electrical graphene-based sensors for bacterial sensing. The analysis is based on comparable findings reported in published studies to identify the main factors influencing sensor performance.

2 | Graphene and Derivatives

Graphene is an allotrope of carbon composed of a monolayer of carbon atoms arranged in a 2D hexagonal lattice that confers its crystalline structure [24]. Graphene is presented in the form of flakes which may or may not have well-defined dimensions, and their size can vary from nanometers to millimeters, depending on the production method [25]. Up to ten carbon monolayers it is still considered graphene, and exceeding this number of layers is recognized as graphite [26, 27]. Graphene can be presented as pristine graphene (pG), graphene oxide (GO), and reduced graphene oxide (rGO) (Figure 1). GO is graphene that has been chemically modified with oxygen atoms, typically containing a C:O ratio of less than 3:1 [28]. The 2D structure of GO exhibits functional groups that lead to a significant change in its properties when compared to pG. Hydroxyl and epoxy groups are randomly

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 | Primary properties of pristine graphene and graphene oxide. Adapted with permission [33]. Copyright 2022, Elsevier.

Property	Pristine graphene	Graphene oxide
Electrical conductivity (S/m)	10 000	0.5
Thermal conductivity (W/m K)	5000	2000
Fracture strength (GPa)	125	0.120
Young's modulus (GPa)	1000	208–230

distributed in the basal plane, while carboxyl, carboxyalkoxy, carbonyl, and phenol groups are located at edges [29]. These functional groups alter both the chemistry and the crystal structure of graphene, introducing various random defects, such as vacancies and holes, which cause deviations from the ideal carbon lattice of Pg [30]. Reducing GO yields graphene with properties similar to those of pG, but it can never reach the same quality since oxidation and reduction processes introduce permanent defects that cannot be restored [31]. These structural permanent imperfections result in a reduction of electrical, optical, thermal, and mechanical properties of rGO when compared to pG. The final chemical and physical properties of rGO depend mainly on the amount of remaining functional groups attached to the graphene structure [32]. The most relevant electrical, thermal, and mechanical properties of pristine graphene and graphene oxide are presented in Table 1. Decreasing values of the properties with the amount of oxygen-containing functional groups evidence the impact of rupturing of the pG crystal lattice. The reduction in electrical and thermal conductivity is due to obstructions in the paths of electricity and heat, while the decrease in fracture strength and Young's modulus is the result of a weakened molecular structure.

2.1 | Electrical Configuration

The molecular structure of pristine graphene is very stable due to strong covalent binding between carbon atoms by sp^2 hybridization. It can withstand deformation by external forces without reconfiguration of atoms. Furthermore, its molecular structure exhibits high crystal quality, which results in unique electrical features that are illustrated in Figure 2 [24]. Due to its electronic band structure, graphene is classified as a semiconductor, where the electric charge can be carried out by electrons or holes. Semiconductors typically have a narrow energy gap between the valence band and the conduction band that differentiate them from conductors and insulators. Figure 2a shows the schematic electronic band configuration of conductors (metal or semimetal), semiconductors, and insulators.

Particularly, pristine graphene stands out as a distinctive material due to its zero-gap electronic band structure that enables its conductor-like behavior [34]. This electronic structure gives graphene inherent carrier ambipolarity. It means that graphene can switch its electrical behavior from electron to hole conduction and vice versa, changing external factors like pressure, voltage, magnetic field, temperature, etc [35]. When charge transport is mediated by electrons, graphene acts as an n-type material; conversely, when holes are the charge carriers it behaves as a p-type material. The energy point where the conduction band and the valence band meet is known as the Dirac point (E_D) and it can be determined by a current–voltage (*IV*) characterization as illustrated in Figure 2b. The typical *IV* curve of ideal pristine graphene that has a continuous V-shape and exhibits E_D around the minimum conductivity point. This parameter is crucial for developing electronic devices as it helps to determine the type of charge carriers and their concentration. It also reveals the interaction with external physical and chemical stimuli [36, 37], which is essential for sensing technology, and it will be discussed in more detail in future sections.

Regarding GO and rGO, its electronic configuration is impacted by the presence of oxygen-containing functional groups and the presence of broken bonds, causing the loss of the unique zero-gap electronic band structure, and consequently the loss of the material ambipolarity [38].

2.2 | Production Techniques

The understanding of how graphene is produced is essential for the development of new technologies, since it determines the final material properties by establishing their dimensions, number of layers, chemical composition, and molecular structure [39]. Production technologies of pristine graphene can be classified into top–down and bottom–up strategies. Top–down techniques consist of mechanical or electrochemical exfoliation of stacked graphene layers from graphite, while bottom–up techniques are based on the synthesis of graphene from carbon sources [40]. Graphite exfoliation is the most widely used manufacturing strategy as it allows the large-scale production of graphene due to the abundance of graphite [41]. Bottom–up strategies have emerged as alternatives to exfoliation because they provide greater control over the final product quality, although production costs are high. Among these strategies, the most studied techniques to produce pG are chemical vapor deposition (CVD) from hydrocarbons on metallic substrates, and epitaxial growth via thermal decomposition of silicon carbide [42]. It is important to note that these methods typically require the transfer of graphene onto other substrates for final applications, as the substrate used in fabrication is not always suitable for the intended use. Another bottom–up manufacturing approach, motivated by sustainability, is the use of organic and plastic waste as carbon sources for the synthesis of graphene [43]. Table 2 shows a summary of the aforementioned production techniques, the size of graphene that can be obtained, advantages and disadvantages, and applications of pG produced by each technology.

The production of GO generally involves the chemical oxidation of graphite and subsequent exfoliation [45]. Hummer's method and its derivatives are the most common techniques used to produce GO. They are based on the use of strong oxidizing agents, such as potassium permanganate, potassium chlorate, or sodium nitrate, to oxidize graphite in an acidic environment [46]. Regarding the synthesis of rGO, chemical reduction of GO is the most widely used technique because it is the most effective [47]. However, this methodology involves the use of toxic agents that may remain in the final product.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

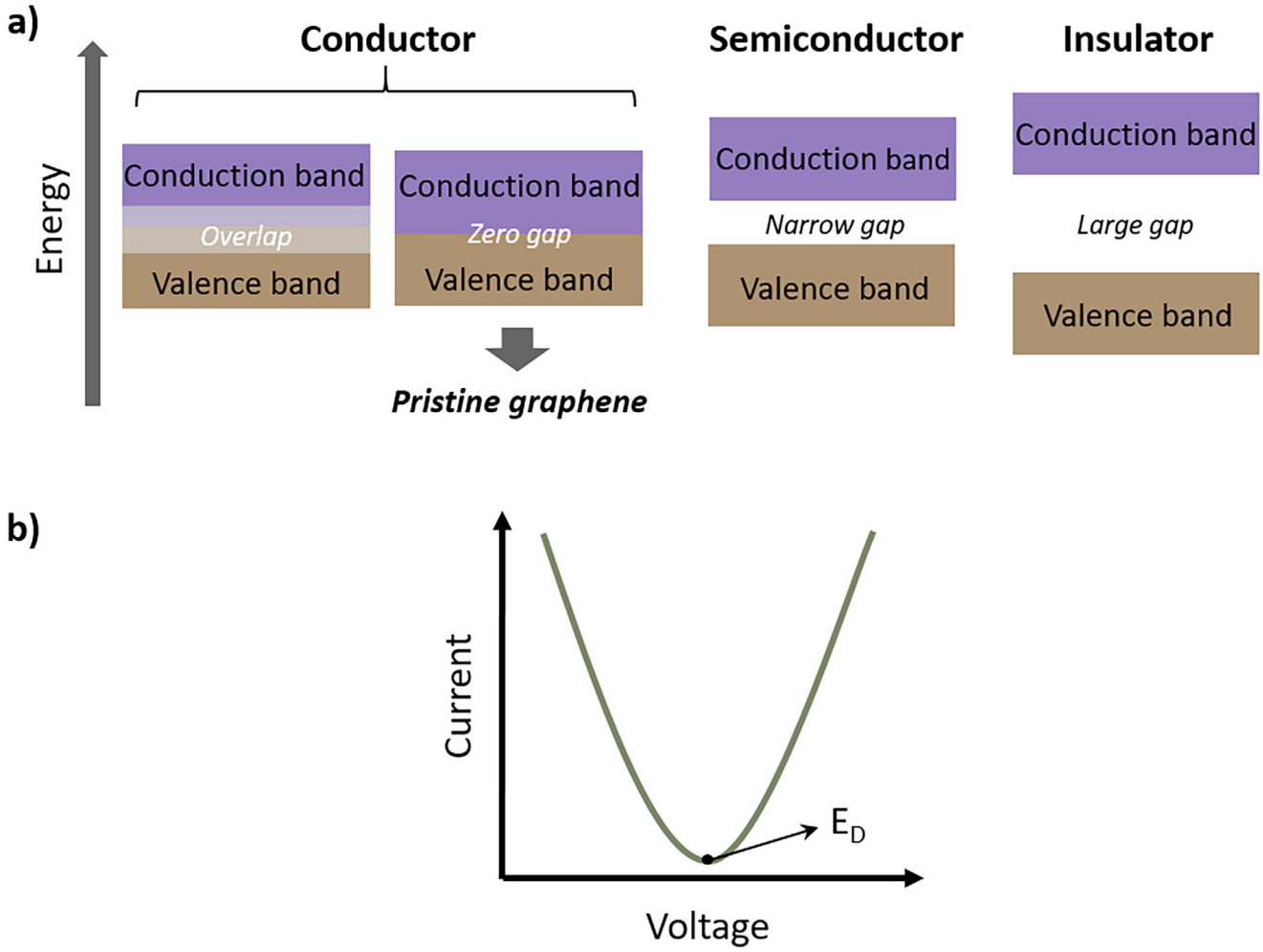

FIGURE 2 | (a) Electronic band configuration of a conductor, semiconductor, and insulator. (b) Typical current–voltage curve of pristine graphene.

In this sense, sustainable approaches such as reduction using microorganisms, biomolecules, and plant extracts have been explored [48].

The existence of various types of graphene and multiple production techniques, with a variety of parameters involved in them, results in a wide range of graphene quality available in the market. Achieving a graphene material with the most suitable properties often means applying a less suitable production process in terms of large-scale production [49]. In this sense, it becomes evident the a need to standardize procedures and materials used in graphene production, as well as to establish quality control protocols. On this basis, the most commonly used techniques for graphene characterization involve microscopy and spectroscopy. Optical microscopy (OM), atomic force microscopy (AFM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Optical microscopy (OM), AFM, SEM, and TEM are widely employed imaging techniques to acquire information on the material morphology and dimensions, as well as on the number of carbon layers [50]. Moreover, Raman spectroscopy (RS) provides information on structural integrity and indicates the presence of oxygen-containing functional groups, meanwhile, X-ray photoelectron spectroscopy (XPS) allows determining the purity of graphene [51, 52].

3 | General Aspects of Graphene-Based Bacterial Electrical Sensors

3.1 | Transfer and Deposition of Graphene

Graphene-based sensor development requires the use of high-quality graphene to obtain a reliable device. CVD graphene is frequently used for this purpose due to its high-quality structure, that leads to the best physical properties, and also a large surface area exposed to the analyte [53]. Even though the CVD technique is promising, it faces challenges for large-scale production, in particular due to the high cost of equipment and materials. Additionally, it is limited to production on specific metallic substrates, such as copper or nickel. To obtain graphene grown by CVD on different substrates, wet or dry transfer techniques have been studied, as schematized in Figure 3. Both techniques are performed by using polymer films that support the graphene to place on the target substrate prior to the dissolution of the metal. In the wet transfer process (Figure 3a), the substrate/graphene/polymer stack is immersed in a proper solvent to remove the transfer polymer film. Dry transfer relies on the difference in adhesion between the graphene/polymer film and graphene/substrate interfaces. Figure 3b shows a transfer polymer film with a pressure-sensitive adhesive layer which is used to support the graphene during the transfer process [54].

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 | Description and main characteristics of pristine graphene production technologies. Adapted with permission [52]. Copyright 2022, IOP Publishing.

	Technology	Description	Flake size	Advantages	Disadvantages	Applications
Top-down strategy	Mechanical exfoliation	Mechanical techniques such as sonication and ball milling, lead to graphite exfoliation.	5–10 nm	- Cost-effective - High-quality graphene layers - Labor saving	- Low process performance - Presence of cracks and defects - Low size uniformity	- Aerospace - Energy-storage devices
	Electrochemical exfoliation	A fixed potential applied onto graphite submerged into an electrolyte with surfactants induces expansion and separation of graphite layers.	2–3 nm	- High-quality graphene layers - Single layer	- Difficulty in removing the surfactant molecules - Low size uniformity	- Supercapacitors - Batteries
Bottom-up strategy	Epitaxial growth	Graphene grows as a consequence of the sublimation of silicium on silicon carbide substrates.	50 µm	- High quality graphene layers - Suitable for electronics	- Highly expensive - Low process performance - Large size - Introduction of voids in the transfer process	- Field effect transistors - Photodetectors
	Chemical vapor deposition	Graphene grows on a metal catalyst in the presence of a carbon-containing gas source at high temperatures.	0.2–10 µm	- High-quality graphene layers - Easy to transfer to other materials - Suitable for electronics	- Highly expensive - High-temperature process	- Light-emitting diode - Biosensors

Although dry transfer techniques have the advantage over wet ones in reducing the number of contaminants added to graphene; the transfer process, independently of the medium, inevitably damages its structural integrity, reducing its ability to conduct electricity [55].

An affordable, scalable, and versatile approach to develop sensors and electronic devices involves the use of graphene inks, based on aqueous or organic solvents, and applying printing technologies such as lithography, spin coating, screen printing, inkjet printing, and direct-writing [56]. A high-quality printing requires not only a high-quality graphene, but also matching the ink characteristics with the surface properties of the substrate and the printing technique. Tran et al. [57] provided an interesting review about the challenges in the synthesis of graphene inks, discussing how the chemical formulations define their final mechanical and electrical properties and determine their stability. Moreover, Zhao et al. [58] offer a complete review describing the chemical and physical interactions of graphene with metals, semiconductors, ceramics, polymers, and biomaterials, which are critical for optimizing ink compatibility with the desired substrate.

3.2 | Sensing Mechanism

Electrical sensors refer to devices whose electrical properties are modified after interacting with the target analyte. The term "electrochemical" has been used interchangeably to denote them in the literature. However, electrical sensors are strictly devices able to perform measurements where no electrochemical reaction occurs [59]. Electrical sensors have a simple structure that consists of at least two elements: a sensitive conductive layer and contact electrodes. The sensing material bridges the gap between the electrodes that can be printed directly on the substrate or on the sensing material, depending on design choices [60]. There are various properties that electrical sensors can measure, including resistance, conductance, impedance, and capacitance [61]. This review focuses particularly on resistive and impedimetric sensors as schematized in Figure 4. Both sensor types quantify the opposition of the sensing material to the electrical current flow, although they operate with different types of current. In resistive sensors, the voltage polarity remains constant, resulting in a unidirectional flow of charged carriers, which indicates the application of direct current (DC). In contrast, impedimetric sensors operate with alternate current (AC), where the voltage polarity periodically changes, causing the direction of charge to alternate accordingly [62].

These sensors operate based on changes in the resistance (Ω) or impedance (Z) of the sensing layer when a direct current (DC) or an alternate current (AC) is applied, respectively. These variations result from chemical or physical processes (adsorption/absorption, chemical reactions, or diffusion) occurring at the surface of the sensing layer. The choice between these transduction mechanisms largely depends on the physical phenomenon

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

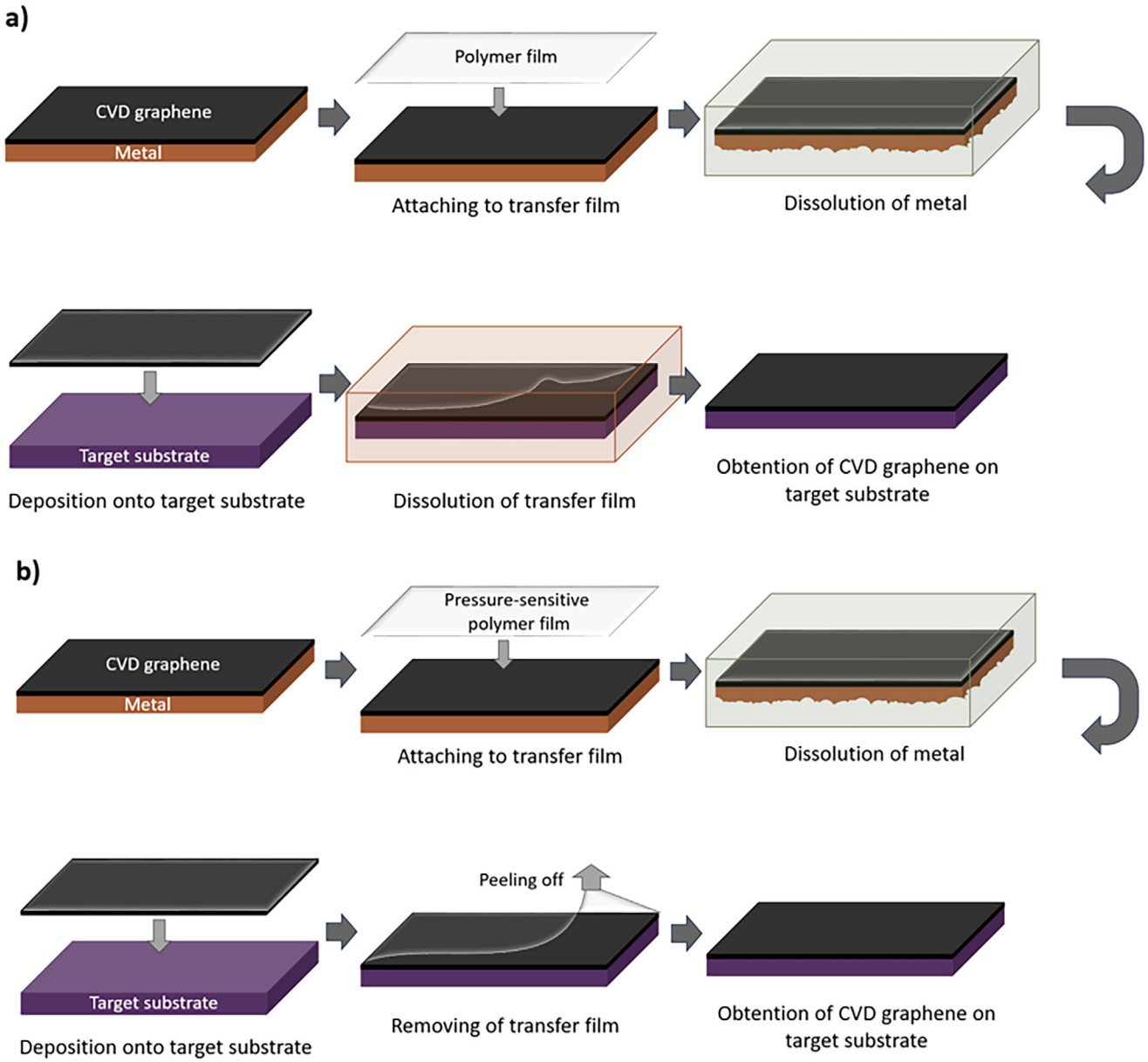

FIGURE 3 | Schematic process of the transfer technique of chemical vapor deposition graphene: (a) wet transfer and (b) dry transfer.

being measured and the complexity of the environment in which the target analyte is present. Although resistive sensors are often preferred for their simplicity, robustness, and straightforward fabrication, their response may be influenced by metal-contact effects and by Joule heating produced during current flow [63]. Since AC current is a quantity more complex than DC current, as illustrated in Figure 4a, impedimetric sensors can provide a richer analysis of interfacial and electrolyte properties through frequency-dependent measurements. However, this increased analytical capability requires more complex instrumentation, making them more sensitive to interference from unwanted molecules and changes in the environment. This demands a more careful analysis of the signal [64].

A deeper level of interaction with the analyte can be achieved by incorporating a third electrode into the device. On example is the field effect transistor (FET), a type of sensor in which the charge carrier density of the sensing material is modulated by an external electric field applied through a third component called the gate electrode. This makes FETs some of the most reliable and versatile devices for sensing applications [65]. It is important to note that FETs are neither purely resistive nor impedimetric sensors because they do not directly measure these variables. However, they can indirectly determine the resistance or impedance of the analyte, along with other parameters. Integrating FET technology into graphene-based sensors utilizes graphene's unique electrical properties, resulting in sensors with high sensitivity, rapid response, and ease of operation [66]. Particularly, the functionalization of graphene-based FET sensors has been widely studied for biosensing applications involving proteins, cells, metabolites, ions [67–69]. Figure 4b shows a schematic diagram of a typical graphene-based FET sensor, detailing its components: the sensing material (graphene) and its three electrodes (source, drain, and gate). The current flows from source to drain electrodes, and the gate electrode regulates the flow of the charge carriers. Although FETs offer exceptional sensitivity due to the direct modulation of

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

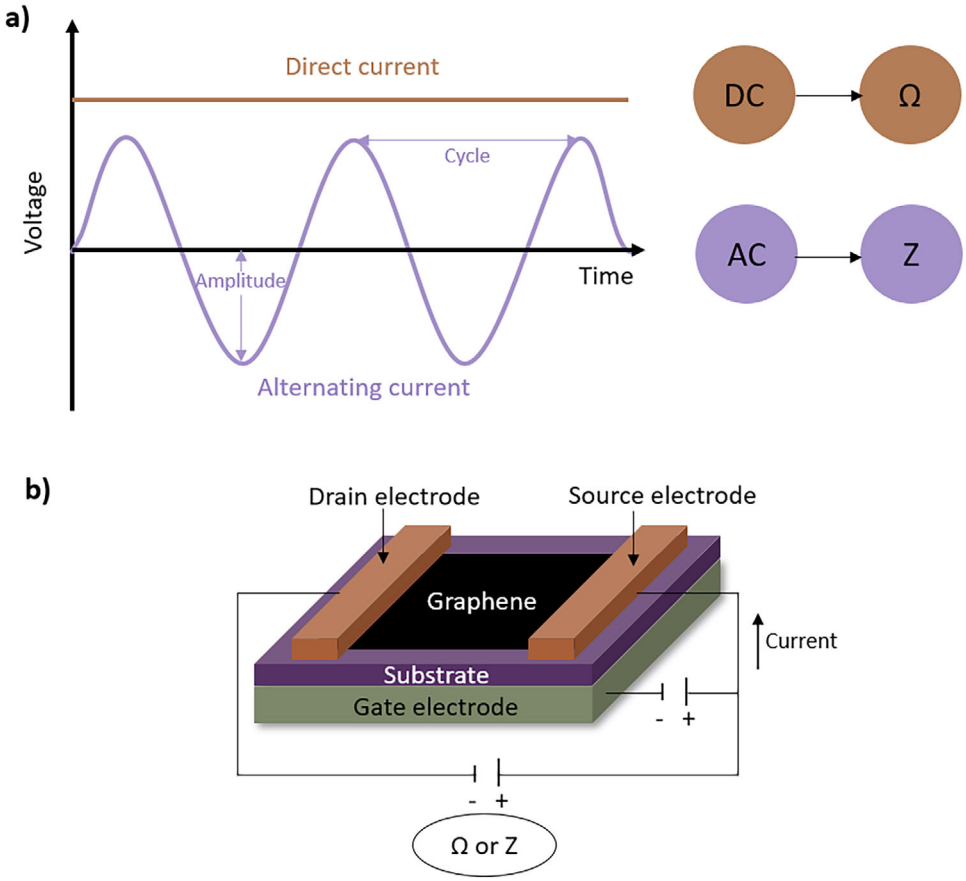

FIGURE 4 | Schematic representation of a resistive and impedimetric sensor: (a) voltage versus time for direct and alternating current, and (b) typical graphene-based field effect transistor.

channel conductivity, their performance can be strongly affected by ionic shielding and operational instability in complex samples [70].

In this sense, selecting between resistive, impedimetric, or FET readouts requires balancing sensitivity, operational robustness, measurement complexity, and compatibility with real biological matrices. It also requires evaluating how each transduction mechanism enhances or limits graphene's intrinsic electrical properties.

3.3 | Graphene-Bacteria Interaction

Non-functionalized graphene-based electrical sensors are a sensing approach in which the graphene itself acts as the conductive sensing layer, with no intermediate agents required to capture the target analyte, such as affinity receptors or bio-recognition elements. These sensors rely on the affinity between the bare sensing layer (graphene) and the analyte and measure their resulting interaction [71]. When the analyte is a bacterial cell, the mechanism of interaction between the cell and graphene is still uncertain. Zhang and Tremblay [72] have explained the factors determining the positive, negative, or undefined impact of graphene on bacteria, being the growth-promoting activity a positive impact, while the antibacterial activity a negative effect. In case of factors with undefined impact, the resulting interaction depends on the circumstances. For example, high specific sheet surface area and roughness increase the number of bacterial contacts, but this may, or may not, lead to good bacterial adhesion depending on several other factors such as the shape and size of bacteria, the density of the exposed sharpen edges of graphene, and the hydrophobicity of the surface, among others. The characteristics of bacteria that influence their adhesion on graphene will be discussed in more detail in subsequent sections.

3.4 | Conventional Bacterial Detection Techniques and Sensing Technologies

In order to provide a comprehensive understanding of the potential of non-functionalized electrical graphene-based sensors, it is essential to describe the conventional and innovative bacterial detection methods. Traditional laboratory-based methods for bacterial detection and identification often require long processing times and lack sensitivity without preconcentration steps. These methods also depend on specialized equipment and trained personnel, which has driven the development of more advanced alternatives [73]. The simplest and most traditional methods rely on cell morphology or biochemical features to identify microorganisms through visual examination. These techniques are typically culture-dependent, involving sample collection, serial dilution, plating on appropriate media, incubation times to produce visible colonies. This process can take from a few days to several weeks, requiring trained microbiologists. Some methods also require biochemical assays such as staining,

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by Cochraneltalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

enzyme production, and antibiotic resistance tests, which involve the use of specific and expensive reagents [74]. More recent conventional techniques based on molecular recognition have reduced processing times and offer greater sensitivity and selectivity. Moreover, these techniques are applicable to a wider range of microorganisms. Sequence-based methods, such as polymerase chain reaction (PCR), detect specific nucleic acid sequences (DNA, RNA, or proteins), while immunological methods, such as the enzyme-linked immunosorbent assay (ELISA), are based on antigen recognition [75]. Although nucleic acid detection typically offers greater selectivity and a faster response than immunological recognition, it requires preprocessing steps, such as cell lysis and target molecule concentration, which implies the use of specific equipment and reagents. In contrast, immunodetection can detect whole cells directly, but the synthesizing and properly selecting the antibodies can be expensive and laborious. Even though these techniques are faster than traditional methods, they can still take several hours to process [76]. The demand for specific, sensitive, rapid, cost-effective, user-friendly bacterial detection technologies suitable for on-site applications has led to the development of biosensors as a promising alternative. A biosensor is a chemical sensing device that incorporates a biological recognition element and a physicochemical transducer. The recognition element, such as a nucleic acid or an antibody, is usually immobilized on the sensing surface, which enables the detection of a specific target [77]. This is referred to as a functionalized sensor, in which a biological molecule acts as an intermediate agent. Biosensors are cost-effective due to their low consumption of biorecognition elements and small sample volumes. They also provide rapid responses and can be used in situ without the need for highly trained personnel. However, there are significant challenges to overcome before this technology can be widely commercialized. These include the limited stability of bioreceptors over time, which makes regenerating the sensor for reuse difficult, and the high specificity required of recognition elements, which limits scalability. Additionally, most biosensors developed thus far exhibit reduced sensitivity when applied to complex real-world samples, such as food. This often requires preprocessing steps that increase both detection time and costs [78]. Table 3 summarizes the most commonly used bacterial detection methods, highlighting their advantages and limitations. This brief overview of bacterial detection techniques emphasizes the need to develop and test new technologies to create a detection system that is highly sensitive and selective, affordable, rapid, and easy to operate. It also highlights the potential of sensing technologies to meet these requirements, motivating further research and development of sensors with novel materials and simple designs, such as non-functionalized graphene-based sensors.

4 | Development of Non-Functionalized Electrical Graphene-Based Bacterial Sensors

4.1 | State of the Art

The first attempt to produce a non-functionalized graphene-based bacterial sensor was made by Daly et al. [79], who presented a detailed procedure for the fabrication and operation of a graphene FET microdevice, along with an initial electrical characterization. The FET device consisted of a sensor used a single-layer CVD graphene as the sensing material, which was dry transferred onto a silica/silicium (SiO_2/Si) substrate using thermal-release tape. Graphene strips were patterned and then contacted by metal electrodes to form the final array, which was then wire bonded to a measuring device for electrical measurements. *IV* characterizations revealed the typical V-shape of the *IV* curve of graphene and a p-type behavior. Electrical measurements were performed to monitor changes in the composition of the nutrients present in a culture medium. Tested solutions, made with different concentrations of lysogen broth (LB), distilled water (DI), and glycerol, were dosed onto the device using a microdispensing system. Glycerol was added to the solution to avoid evaporation of the drop. Electrical tests showed an increase in resistance with LB concentration. A shift in the Dirac point from positive to negative values was observed when graphene was in contact with LB medium, indicating a change in carrier type from holes to electrons due to the doping of graphene with electrons from adsorbed molecules. To prove the device biocompatibility, *E. coli* was dispersed on it, and the surface was observed by SEM. An increase in cell density on the graphene array after one day, demonstrated the sensor compatibility for bacterial applications. Additionally, a test was performed to analyze the influence of the graphene transfer technique on the FET response. The same experimental procedure was carried out using a new device where graphene was transferred onto the substrate via a wet transfer method. This new approach minimized the mechanical damage to the graphene caused by using thermal release tape in the transfer process. Once again, an increment in the resistance with increasing concentration of LB was observed, indicating no significant changes in the sensor response. However, the bare new sensor exhibited clear changes on its *IV* curve since no Dirac point was observed, revealing an alteration of the graphene electronic configuration. Summarizing, the observable increase in electrical resistance of the sensor with LB concentration validated the use of FET devices for detecting changes in a complex liquid system used for cell proliferation and demonstrated their compatibility for bacterial applications. Furthermore, this attempt highlighted the importance of optimizing the sensor fabrication process to achieve the desired electrical properties in the final device.

The sensing abilities of non-functionalized graphene in the presence of *E. coli* cells have been studied by Rao et al. [80] using monolayer, bilayer, and few-layer exfoliated graphene. All graphene samples were produced by mechanical exfoliation from highly oriented pyrolytic graphite and then directly transferred onto SiO_2/Si substrates. Each graphene sample was cut into a regular shape, and metal electrodes were deposited on it to complete the assembly of the resistive graphene-based sensors. Rao et al. [80] developed devices with two different electrode configurations: a four-probe sensor and a two-probe sensor. For the bacterial loading process, *E. coli* cells were dispersed in DI water to obtain bacterial solutions with different cell concentrations. These solutions were deposited on the graphene sensing surface, and the devices were heated to avoid liquid contribution and ensure better cell attachment. The first analysis was conducted using a few-layer graphene-based sensor with four electrodes printed on it that allows to study the influence of the crystallographic orientation of graphene. The electrical measurements for this sensor were conducted using different electrode pairs aligned with different structural orientations of graphene. *IV* measurements showed an increase in resistance when bacteria

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 3 | Conventional bacterial detection techniques and biosensors: Description, advantages, and disadvantages.

Technique	Description	Advantages	Disadvantages
Culturing and biochemical assays	Identification based on bacterial growth, morphology, and biochemical properties.	- Simple - Cost-effective	- Time-consuming (days to weeks) - Lab dependent - Requires experienced operators - Not applicable to all strains - Specific and expensive reagents
Nucleic acid sequenced-based detection	Detection of specific DNA or RNA sequences of target bacteria.	- High selectivity and sensitivity - Rapid response (few hours) - Adaptable to on-site detection	- Requires preprocessing to expose and concentrate the target - Expensive equipment and reagents
Immunological detection	Detection of bacterial antigens using antibodies.	- Moderate selectivity - Direct whole-bacteria detection - Adaptable to on-site detection	- Low sensitivity - Expensive and laborious synthesis of antibodies - Time-consuming (several hours)
Biosensing detection	Capture and detection with biological recognition molecules.	- High selectivity - Very rapid response (minutes) - Direct whole-bacteria detection - On-side testing	- Limited stability of bioreceptors - Difficulties in reuse - Low sensitivity in complex samples without preprocessing - Scalability limitations

were attached to graphene. The magnitude of the responses varied depending on the considered electrode pair, indicating that crystal orientation played an important role in the sensitivity of graphene devices. To further investigate the sensor sensitivity, individual *E. coli* cells were loaded onto the graphene surface of few-layer and monolayer graphene-based sensors with only two electrodes on each. Both sensors showed a measurable response even with one cell, but the recorded magnitudes depended on the number of graphene layers. Monolayer graphene had a change in resistance five times higher than the few-layer graphene when one cell was loaded. This was expected since the entire sensing surface on a monolayer graphene is in direct contact with the bacteria. Another test was conducted using a bilayer graphene strip with a width approximately matching the size of bacteria (around 1 to 3 μm). Since it is well known that nanoribbon-like graphene structures exhibit enhanced electrical properties due to charge confinement, similar behavior was anticipated for the micro-ribbon. In fact, the response of a bilayer graphene-based device to one cell was two times higher than the one obtained with a monolayer surface. The electrical response of all devices was attributed to the negatively charged cells that act as trap centers for the holes in the p-type graphene, reducing its conductivity. This study was very promising as it demonstrated that a one-cell resolution sensor could be developed. Additionally, it showed that the number of layers significantly impacts the sensitivity of the sensors as well as the crystallographic orientation of graphene.

Basu et al. [81] proposed a flexible impedimetric graphene-based sensor. For this device, a multilayered CVD graphene was produced and then wet transferred onto flexible and transparent acetate sheets. Metal electrodes were deposited on graphene to form an integrated electrode structure, and an acrylic O-ring was added to create a well to contain the analyte solution. *E. coli* was grown in LB medium, and cell suspensions with different concentrations of bacteria were used as analyte solutions to evaluate the sensor performance. Prior to the electrical measurements, bacterial solutions were deposited inside the O-ring to allow cell binding for a 10-minute exposure, then the liquid was manually removed to avoid its current contribution. Impedance measurements were carried out to examine the electrical response of the bare substrate and the sensor exposed to the different *E. coli* solutions. No significant response was observed with the bare substrate. However, a decrease in impedance with increasing cell concentration was detected for the graphene-based sensor, indicating the sensing capability of the device. In order to confirm *E. coli* adhesion, the bare substrate was stained and examined by OM. Micrographs revealed that no bacteria adhered to the bare acetate sheet, while a large number of cells were bound to the graphene surface. In order to better understand the cell attachment mechanisms, Fourier transform infrared spectroscopy was conducted on the sensing device, revealing the presence of residues from the transfer process that could not be completely removed. Thus, the increase in impedance with bacterial concentration was attributed to the negative charge of the *E. coli* cells that induced holes in graphene when adsorption occurred on residues that acted as binding sites for bacteria. This work highlighted the versatility of graphene for the construction of flexible sensors. Furthermore, it revealed the contamination of graphene during the transfer process and demonstrated that some of these residues can positively impact the sensing performance by facilitating bacterial adhesion.

Mulyana et al. [82] presented a detailed study on the alteration of graphene ambipolarity after the adsorption of *E. coli*. For this purpose, a graphene-based FET was developed using exfoliated graphene obtained via micromechanical exfoliation of kish graphite, a highly crystalline form of graphite naturally produced as a by-product of stainless-steel manufacturing. This graphene was directly deposited on a SiO_2/Si substrate and connected to metal electrodes to complete the assembly of the device. The *IV* curve of this pristine graphene showed a V-shaped behavior, demonstrating its intrinsic ambipolarity. For this study,

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

E. coli was grown in LB medium and resuspended in pure water before dropping it on the device. After 30 min, the aqueous solution naturally dried, and electrical measurements were performed under vacuum and anaerobic conditions to suppress the metabolic activity of bacteria. The *IV*-curve remained V-shaped, but important changes associated with bacterial adhesion were appreciable. The Dirac point shifted positively due to the physical adsorption of the *E. coli* cells that induce holes, indicating an increase in the amount of charge. Moreover, the increasing gradients of the *IV* curve suggested an increase in electron mobility, attributed to the protective layer formed by bacteria, which suppressed electron scattering. For a better understanding of electrical results, a comparative study of ambipolarity was performed by oxidizing the graphene surface and then reducing it, to restore its properties close to the pristine state. A decrease in the gradient of the *IV* curve of the oxidized graphene indicated a reduced electron mobility due to the presence of oxygen-containing functional groups that obstruct the path of electrons and increase the scattering. After the reduction process, an increase in electron mobility was observed. The physical adsorption of *E. coli* was confirmed since there was no decrease in electron mobility, and no metabolic bacterial activity could interfere with the results due to the low pressure and anaerobic environment. This work demonstrated that examining the ambipolarity of graphene provides a deeper understanding of the processes involved in bacterial detection using graphene-based devices.

With the aim to develop a resistive sensing device for detecting *E. coli* in wastewater samples, Wibowo et al. [83] investigated the electrical response of commercial multilayer CVD graphene deposited on a SiO_2/Si substrate. For electrical measurements, a pair of metal electrodes was attached to graphene, completing the development of the sensor. To assess the bacterial response of the sensing device, *E. coli* was obtained directly from wastewater samples. These cells were identified and isolated before preparing analyte solutions with different known concentrations of bacteria. *IV* response of the sensor to bacterial samples showed that an increase in the number of cells resulted in a decrease of the graphene electrical resistance. Moreover, the analysis of graphene exposed to bacteria by Raman spectroscopy indicated that higher concentrations of cells induced greater disorder or defects in graphene, attributed to the absorption of negatively charged *E. coli* cells that create holes. Based on their previous work, Wibowo et al. [22] disclosed a more detailed study of bacteria-graphene compatibility and the development of a prototype of a portable and compact sensor. The same commercial CVD multilayer graphene used in Wibowo et al. [83] was characterized to study the susceptibility of bacteria to graphene exposure. A compatibility test was performed by incubating an agar plate with *E. coli* and graphene. With this test, the antibacterial activity can be determined by observing the presence of bacterial growth inhibition zones. As expected, no inhibition zones were observed on the agar plate with graphene, indicating its biocompatibility. Moreover, a wettability test was performed by contact angle measurements on bare graphene, revealing the hydrophobic nature of graphene which is favorable for bacterial adhesion. Bare graphene exhibited a smooth surface and a uniform surface area, being essential for optimal electrical measurements. SEM micrographs of bacteria deposited on the graphene surface after one day of exposure revealed well-preserved *E. coli* colonies with no signs of cell membrane damage. For electrical measurements, suspensions of *E. coli* in DI water with different concentrations were analyzed. The sensor performance was studied by placing a drop of bacterial solutions onto the graphene sensing layer and measuring the signal after liquid evaporation. The *IV* results revealed a charge transfer between graphene and *E. coli*, causing a decrease in resistance that could be attributed to the negatively charged *E. coli* cells that induce holes in graphene, as previously reported. It was assumed that van der Waals forces governed the interaction between the hydrophobic part of the outer cell wall and the surface of the sensing layer. The linear behavior of the *IV* curves indicates the expected semi metallic nature of graphene and suggests the formation of a low-electrical resistance contact between graphene and the electrode. The final sensor prototype was assembled in a compact and portable device designed with 3D modeling software. This research demonstrated the possibility of constructing portable graphene-based sensors for in situ detection of bacteria in wastewater.

An interesting advance in exploring the sensing capabilities of graphene for bacterial detection was achieved by Pandit et al. [23] since they studied the electrical response of graphene to two different bacterial strains. A CVD monolayer graphene was produced and wet transferred onto a SiO_2/Si substrate. Four metal electrodes were printed on the substrate to develop an FET sensor. Graphene was patterned into a small bar-shape structure, and then a protective layer was applied over the entire surface except the graphene structure, creating a submersible device. Electrical measurements on bare graphene revealed its p-type behavior attributed to chemical residues by the transfer method. Bacterial tests were conducted individually using *Pseudomonas aeruginosa* (*P. aeruginosa*) or *Staphylococcus epidermidis* (*S. epidermidis*). LB medium was used to grow *P. aeruginosa* (rod-shape and gram-negative bacteria), while tryptic soy broth (TSB) was selected as growth medium for *S. epidermidis* (spherical cocci and gram-positive bacteria). Electrical resistance was continuously monitored while the sensor was dipped in both culture media, with and without bacteria. All experiments were performed under optimal incubation conditions. After 5 h, an antibiotic solution was added to the tested solutions to kill bacteria, and the measurement continued for an additional 3 h. For both culture media without bacteria, electrical resistance increased initially and then remained relatively stable until an antibiotic was added. The antibiotic induced a slight increase in resistance, followed by a stable signal for the last 3 h. When bacterial solutions were tested, a continuous linear increase in resistance with colony-forming units (CFU) was observed for *P. aeruginosa*, followed by a sharp saturation. In contrast, the resistance behavior with CFU was more complex for *S. epidermidis*, with local minimums and maximums. This behavior was attributed to the different growth dynamics and biofilm formation of the different bacteria, leading to variations in the density of the adhered microcolonies on graphene. Bacterial growth was confirmed by the observation of biofilm presence on SEM micrographs. Although both bacteria produced biofilm, their characteristics differed significantly. For *P. aeruginosa*, most cells were in the single-cell stage, with few multicellular clusters, while *S. epidermidis* cells were predominantly in large multicellular clusters. As observed previously, the antibiotic induced an increase in resistance followed by a stable signal, suggesting that dead bacteria did not alter the electrical

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 4 | Summary of key findings and illustrations of non-functionalized graphene-based electrical sensors for bacterial detection (2012–present).

Year	Type of sensor	Analyte	Key findings	Illustration of the sensor	Refs.
2012	FET	LB medium	- Validation to detect changes in the composition of bacterial culture medium - Demonstration of the influence of the graphene transfer process on the sensor electrical behavior		[79]
	Resistive	*E. coli* in DI water	- Study of sensor sensitivity based on the number of layers and geometry of graphene, as well as electrode arrangement - Validation of single-bacterium detection		[80]
2014	Impedimetric	*E. coli* in LB	- Development of a flexible sensor - Evidence that residues of the transfer process of graphene can enhance bacterial adhesion		[81]
2018	FET	*E. coli* in pure water	- Analysis of changes in the *IV* curve and ambipolarity for chemical reactions (graphene oxidation) or physical adsorption (*E. coli* adsorption)		[82]
2020	Resistive	*E. coli* in DI water	- Validation of a portable sensor design for in situ measurements		[22]
2021	FET	*P. aeruginosa* in LB *S. epidermidis* in TSB	- Study and validation of graphene selectivity for detecting different bacteria. - Construction of a submersible sensor for real-time monitoring		[23]
2022	Impedimetric	*E. coli* in LB	- Detection and monitoring of biofilm formation - Analysis of sensor responses at different frequencies		[84]

signal. This study highlighted that graphene can be intrinsically selective, as evidenced by the different electrical responses of the sensor to two species of bacteria that differed markedly from one another.

In addition to sensing cell suspensions, it is crucial to test the graphene ability to monitor biofilm formation. To this aim, Nakagawa et al. [84] developed an impedimetric sensor using CVD graphene deposited on a copper substrate. Mono- and bilayer graphene were initially characterized using impedance measurements that yield impedance-frequency curves. For these electrical measurements, graphene samples were positioned between two copper plate electrodes contacted by an insulating organic substance to form the measurement system. *E. coli* bacteria were grown in LB medium to produce biofilms on the graphene surface. After 24 h, biofilm formation was confirmed in both mono- and bilayer graphene. Quantification of biofilm was performed by absorbance analysis of the stained samples. These tests revealed a higher biofilm amount on monolayer graphene compared to bilayer samples. Furthermore, impedance studies revealed that the presence of biofilm altered the impedance behavior of graphene, particularly at high frequencies. Prior to biofilm formation, the impedance of graphene decreased with frequency, while an increase in impedance with frequency was observed when biofilm was present on the graphene surface. This behavior is attributed to the alteration in the electric pathway by varying frequencies. At lower frequencies, ionic conduction in the aqueous solution was more favorable, whereas at higher frequencies the current tended to move to areas with a higher concentration of extracellular polymeric substances from the biofilm. This study suggested that alterations in the impedance of graphene at high frequencies could be crucial to indicate the presence of biofilm and subsequent bacterial colonization.

Table 4 summarizes studies from 2012 to 2022 on non-functionalized graphene-based electrical sensors for bacterial detection, reporting sensor type, target analyte, key findings, and a representative illustration of each device. This compilation highlights common trends and distinctive features in sensor development, supporting the critical discussion in the following section on design and operational factors that influence performance.

4.2 | Sensor Constructive and Operational Challenges

Developing a reliable, non-functionalized sensor requires a thorough understanding of the interaction between the analyte and

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

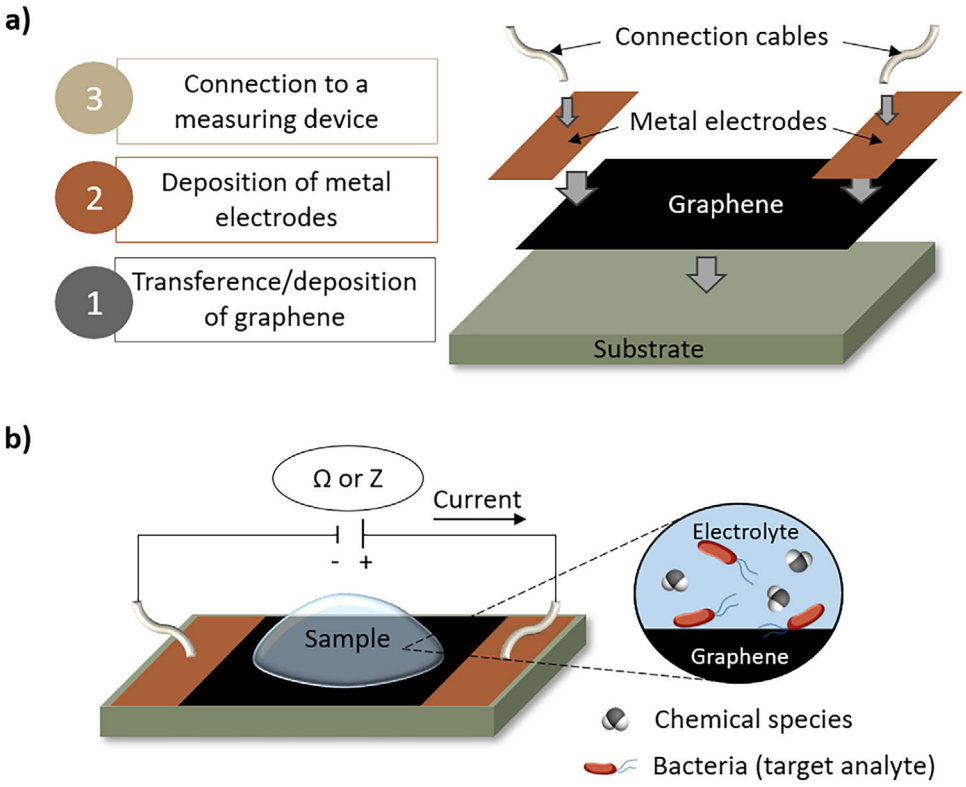

FIGURE 5 | Illustration of: (a) construction and (b) operation of electrical graphene-based bacterial sensors.

the sensing platform. Therefore, it is essential to determine the surface properties of both graphene and bacteria to understand their interaction. Moreover, it is important to study the influence of the sensing device development process of and environmental factors that may affect sensing measurements. Figure 5 illustrates the construction and operation of a typical electrical graphene-based bacterial sensor, which helps comprehend the discussion in this section. Figure 5a shows the main materials and procedures involved in developing the sensor, while Figure 5b shows an operational sensor and details about the liquid sample to be measured.

4.2.1 | Bacterial Adhesion on Graphene

Bacterial adhesion to graphene is a multifactorial process governed by the interaction between the physicochemical properties of the graphene surface and the intrinsic characteristics of the bacterial cells. There is no single surface characteristic that is more relevant than the others, thus when developing bacterial sensors, it is important to consider all factors. The main mechanisms of interaction between bacteria and graphene are schematized in Figure 6.

4.2.1.1 | Graphene Surface Characteristics. The key properties of graphene that favor the initial bacterial adhesion include surface characteristics such as charge density, wettability, roughness, stiffness, and topography (Figure 6a). Zheng et al. [85] presented a comprehensive review outlining the typical bacterial responses to each of these graphene features. The main forces driving bacterial attachment are van der Waals forces and electrostatic interactions. Given that bacteria possess a negatively charged cell wall, increased adhesion is observed on positively charged surfaces. The wettability of graphene, which is primarily governed by its surface energy and roughness, is another crucial property since it influences the contact area with biological samples. However, having a large contact area does not guarantee bacterial attachment. In the presence of a liquid medium that usually forms part of the biological systems, ionic strength also participates in the complex interaction between graphene and bacteria. In addition to affecting wettability, the surface roughness of graphene offers anchor points and protection for already attached bacteria, promoting both adhesion and biofilm formation. In some cases, ultra-rough surfaces lead to reduced bacterial adhesion due to a decrease in contact area between bacteria and graphene, as well as the mechanical disruption of bacterial cell membranes caused by the sharp nano-edges of graphene sheets [86]. Regarding surface stiffness, it has been observed that softer surfaces exhibit higher retention and stronger adhesion under external shear stress. Surface topography is another critical factor since bacteria are capable of sensing and responding to surface structures. They tend to align along valleys and pillars to maximize their attachment area, prioritizing grooves between protruding features. Surfaces with structural features larger than the size of a single bacterium provide greater contact area and shelter, leading to enhanced bacterial attachment. Notably, the topographical features of graphene-based sensing platforms can be customized by printing graphene patterns to optimize bacterial adhesion for sensing applications [87].

4.2.1.2 | Bacterial Characteristics. The bacterial characteristics that influence adhesion are essentially cell wall components, appendages, and motility. Kreve and Reis [88] provided

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

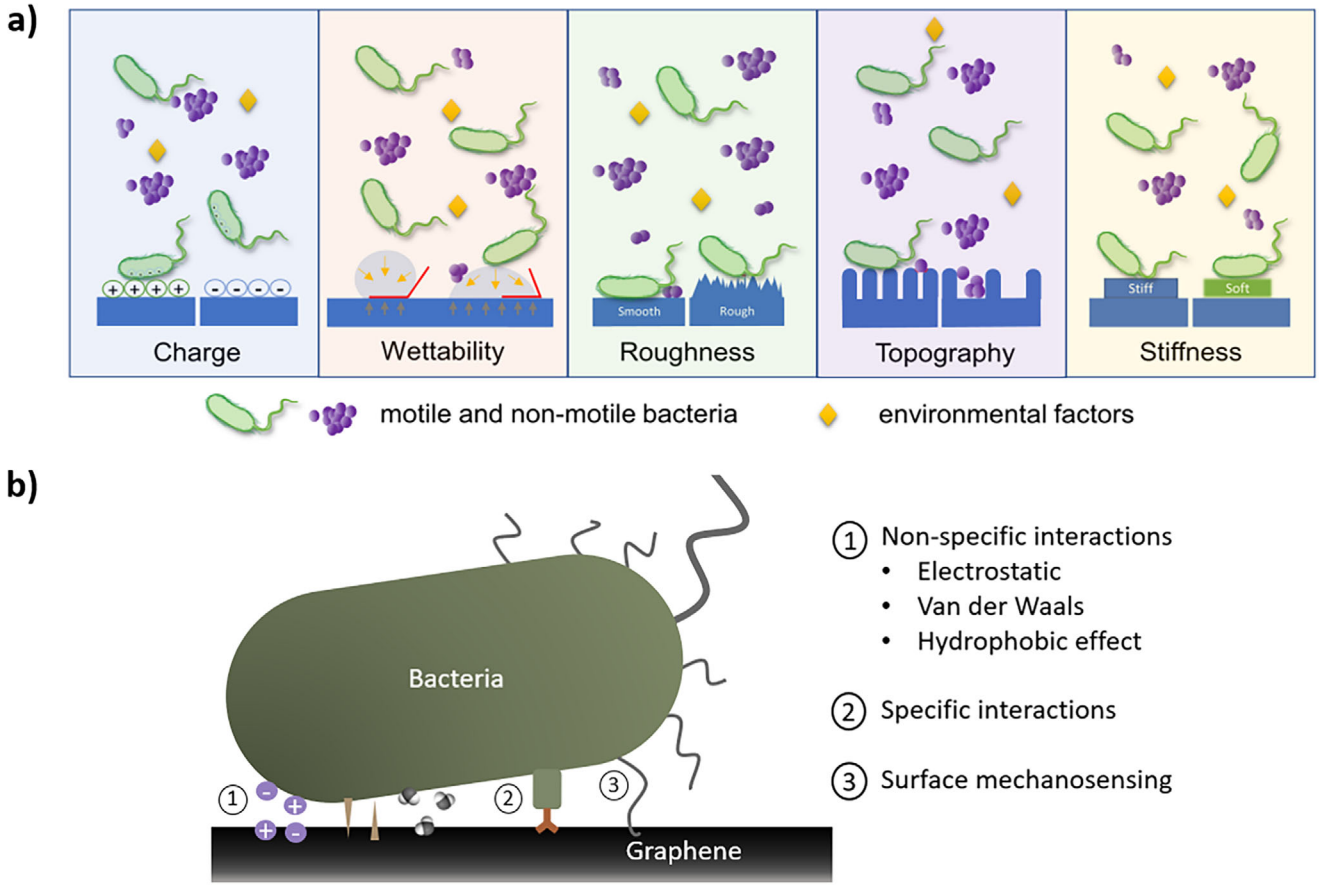

FIGURE 6 | Schematic representation of: (a) graphene's surface factors that influence bacterial adhesion. Reproduced with permission [85]. Copyright 2021, Frontiers, and (b) adhesion mechanisms between bacteria and the graphene surface.

a comprehensive review detailing the mechanisms underlying bacterial surface adhesion. The interactions involved can be categorized into non-specific physicochemical interactions, specific interactions, and surface mechanosensing (Figure 6b). In the case of non-specific interactions, adhesion occurs through van der Waals forces, electrostatic charges, and the hydrophobic effect between the bacterial cell wall surface, appendages, and the sensing surface. Specific interactions involve appendages that can recognize and bind, through a chemical reaction, to particular molecules present on the graphene surface. This mechanism was highlighted by Basu et al. [81] that demonstrated that the bacterial graphene-based sensor they developed retained polymer residues from the transfer process, which serve as binding sites. Last, surface mechanosensing refers to the active detection by appendages of physical features of the sensing surface. Appendages play a crucial role in bacterial adhesion due to their small diameter, which allows them to overcome repulsive electrostatic interactions. Moreover, appendages can be equal to or greater in length than the bacteria themselves, enabling them to detect mechanical signals from a distance. A demonstration of the impact of bacterial properties is shown in Figure 7, which illustrates the individual responses of the graphene-based sensor developed by Pandit et al. [23] to different bacteria. Figure 7a reports the response of *P. aeruginosa*, showing an increase of resistance with CFU until a maximum point. In contrast, Figure 7b presents the sensor response for *S. epidermidis*, evidencing a more complex behavior associated with different growth dynamics that lead to changes in the environment.

4.2.2 | Electrical Response

4.2.2.1 | Graphene Molecular Structure Influence. Even though the properties of graphene and bacteria that influence bacterial adhesion have been discussed, it is crucial to analyze the impact of the sensing device development on the sensor response. Particularly, for electrical sensor development, a deep comprehension of the electrical properties of the device is necessary. As mentioned in previous sections, the properties of graphene depend on its type and production method. Given that graphene is a zero-bandgap semiconductor, its electrical configuration is highly sensitive to external factors. The introduction of contaminants and the creation of structural defects are the major sources of changes in the electrical behavior of graphene-based sensors. Daly et al. [79] analyzed the *IV* curves of graphene-based sensors, which they developed using different transfer techniques, demonstrating the impact of contaminants and defects. The first sensor was fabricated using a dry transfer method with thermal-release tape, while the second sensor was developed through a wet transfer method to mitigate mechanical damage associated with the use of thermal-release tape. Figure 8 shows the *IV* curves obtained for these sensors for different mediums (DI water and LB medium). The first development approach

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

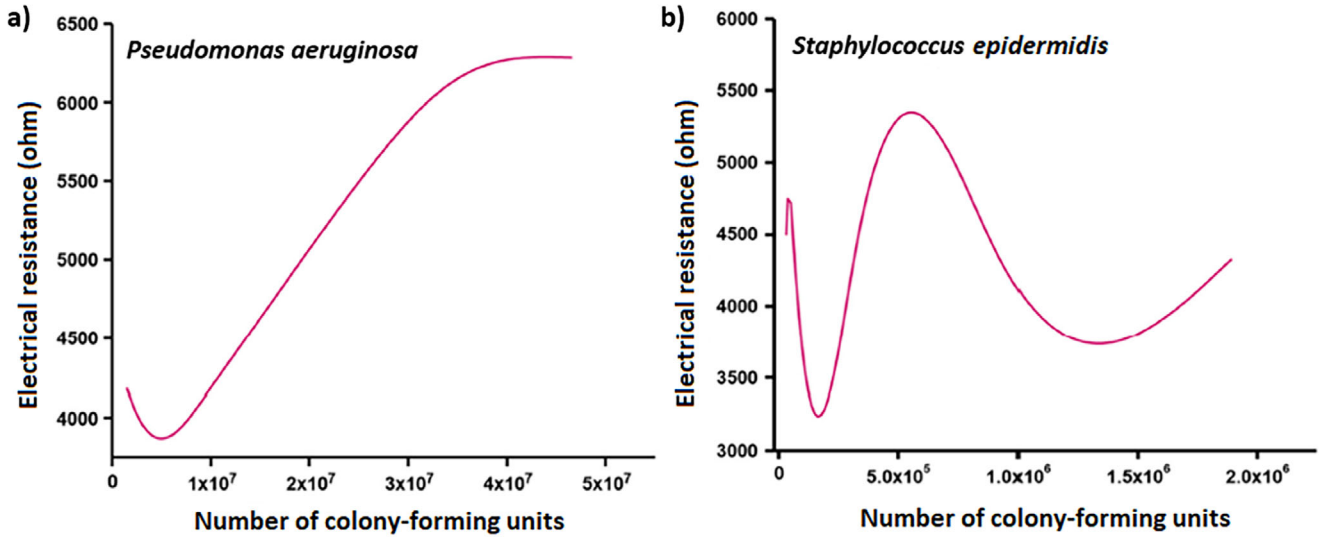

FIGURE 7 | Electrical resistance versus number of colony-forming units for: (a) *Pseudomonas aeruginosa* and b) *Staphylococcus epidermidis*. Reproduced with permission [23]. Copyright 2021, MDPI.

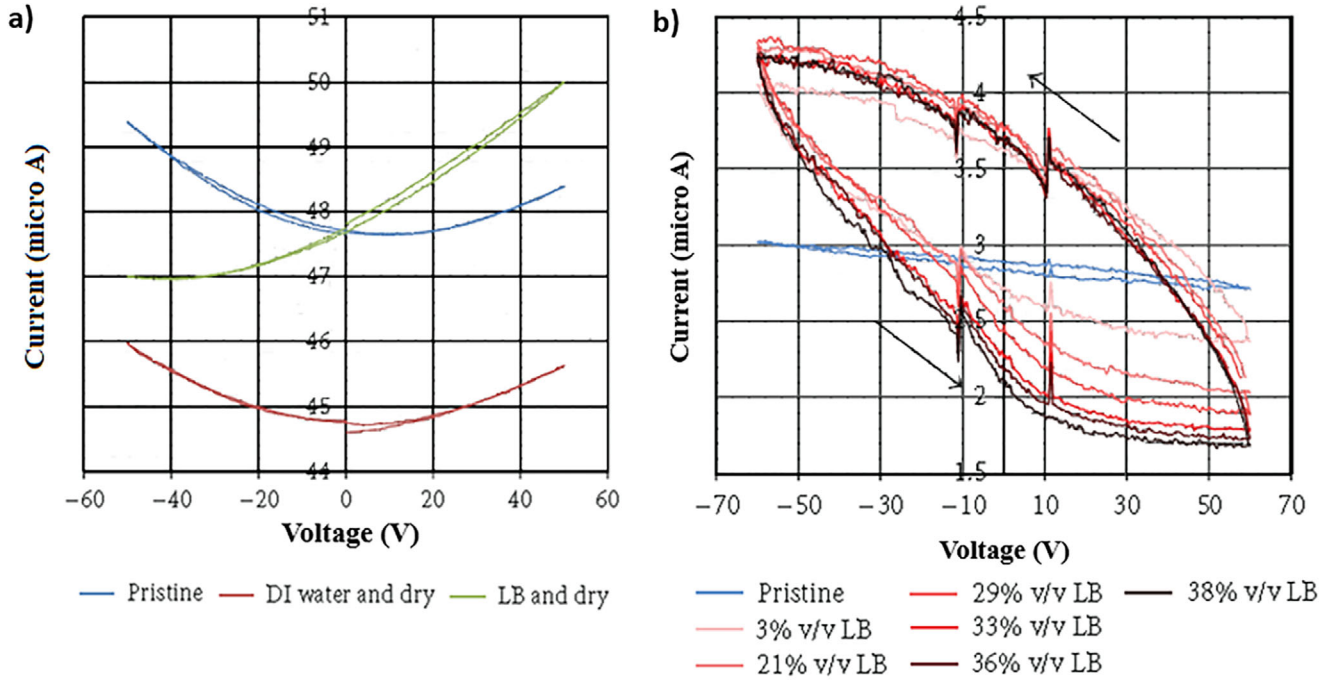

FIGURE 8 | Current–voltage curves for the graphene-based sensors developed through a: (a) dry transfer, and (b) wet transfer techniques. Reproduced with permission [79]. Copyright 2012, Wiley.

displayed an *IV* curve with the expected V-shaped characteristic (Figure 8a). In contrast, the second approach resulted in different electrical behavior, where the Dirac point is not observable, and hysteresis cycles become prominent, especially during analyte measurement (Figure 8b). These results highlight the effects of contaminants and defects. Defects typically act as obstacles to the movement of charge carriers, leading to a decrease in conductivity; however, they cannot be interpreted independently. Although the second sensor was designed to avoid mechanical damage, its conductivity did not improve and, in fact, worsened, as evidenced by comparing the current scales of the *IV* curves for both sensors. Furthermore, a shift from the intrinsic *IV* curve of graphene is observable, elucidating the predominant impact of contaminants introduced during the wet transfer process.

4.2.2.2 | Graphene-Analyte Electron Exchange. Understanding the role of molecules that interact with graphene is not only essential for detecting contaminants in the sensor, but it is also critical for interpreting the response of the electrical sensor when exposed to analytes. Pristine graphene has its Dirac point that aligns with its Fermi level (E_F), the highest energy state that an electron can occupy at 0 K. When electron-donor or electron-acceptor molecules adsorb onto graphene, E_F increases or decreases, respectively [89]. In the case of electron-donor

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

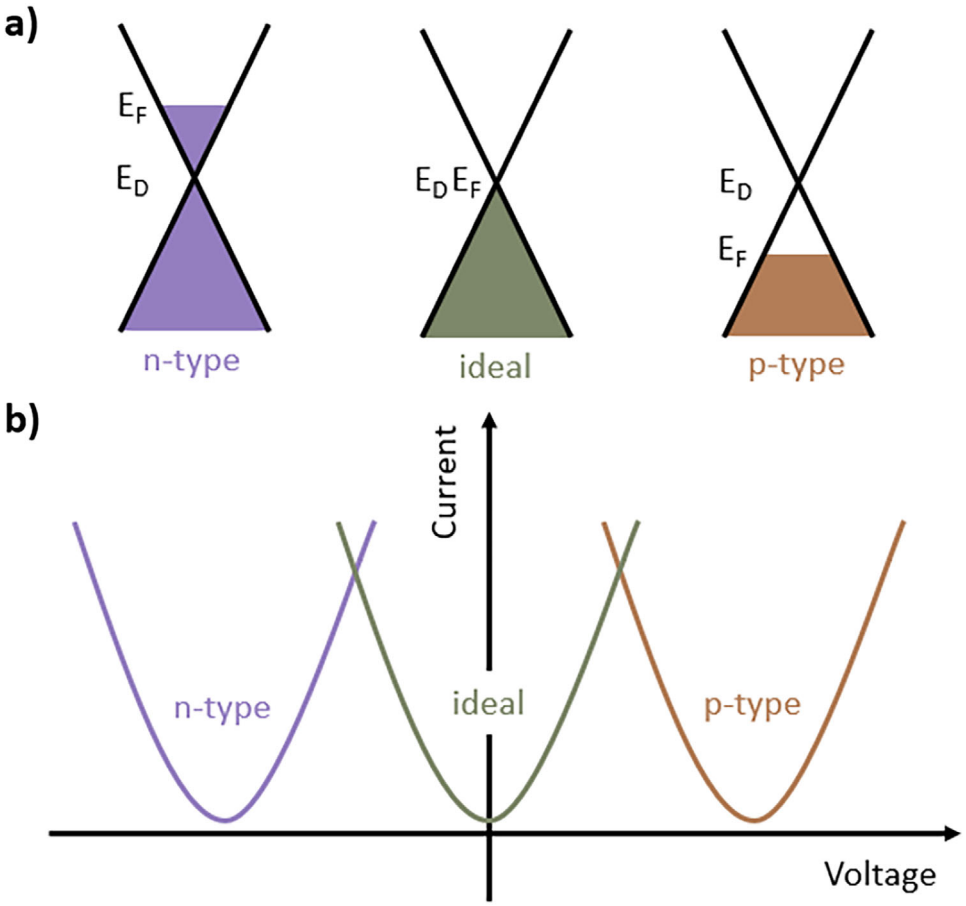

FIGURE 9 | Electronic characteristics of ideal pristine graphene, n-type graphene, and p-type graphene: (a) energy band diagram and (b) representative *IV* curves.

molecules, the increase in electron density causes graphene to behave as an n-type semiconductor, where electrical conduction is mediated by electrons. Conversely, electron-acceptor molecules induce p-type behavior in graphene, where conduction is driven by holes. Figure 9 illustrates the band diagrams and characteristic *IV* curves for n-type, ideal, and p-type graphene. Analyzing the energy band diagram of n-type graphene reveals that its E_F is higher than E_D, while for p-type graphene, E_F is lower than E_D. Under ambient conditions, graphene typically behaves as a p-type material. When p-type graphene is exposed to electron-donor molecules, these molecules donate electrons, which fill the holes and consequently reduce its conductivity. On the other hand, if electron-acceptor molecules adsorb onto p-type graphene, they remove electrons, increasing conductivity. These variations can be detected by analyzing the *IV* curves of graphene. Figure 9b represents the typical *IV* curves for ideal pristine graphene, n-type graphene, and p-type graphene. The *IV* curves of the graphene-based electrical sensor developed by Daly et al. [79], as shown in Figure 8a, confirm that pristine graphene exhibits p-type behavior. When the sensor is exposed to DI water, no molecules are adsorbed on the graphene surface, and the observed increase in current is attributed to exposure to the electrolyte. However, when the sensor is exposed to pure LB, a shift in E_D occurs, which is attributed to the adsorption of phosphoproteins present in the analyte that act as electron–donor molecules.

4.2.2.3 | Bacterial Metabolism Influence. The electrical behavior of bacteria is more complex than that of other molecules, as bacteria are living cells with metabolisms that can interact with the sensing material. In the bacterial respiratory process, electron transport across the cell membrane is mediated by electron acceptor molecules in both aerobic and anaerobic respiration [90]. The electron exchange between bacteria and graphene can have a significant impact, potentially leading to chemical reactions that alter the material itself. It has been demonstrated that several bacteria, such as *Shewanella*, *Lactobacillus*, and *E. coli*, are capable of reducing graphene oxide through their respiration processes [91–93]. This evidence shows the importance of distinguishing whether bacteria induce chemical modification of the sensing material in graphene-based sensors. In this sense, Mulyana et al. [82] compared the *IV* curves of graphene-based electrical sensors before and after exposure to *E. coli*, and before and after oxidation via UV/O_3 treatment, to identify changes related to chemical reactions on the sensing material. It has been demonstrated that when the sensor was exposed to *E. coli*, no decrease in conductivity was observed in the *IV* curves, indicating that the bacteria did not chemically react with graphene, but only physical adsorption occurred. However, when graphene was oxidized, a significant decrease in conductivity was observed as a consequence to the oxygen-containing functional groups that obstruct the path of charge carriers. It is important to note that these tests were conducted under vacuum conditions,

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

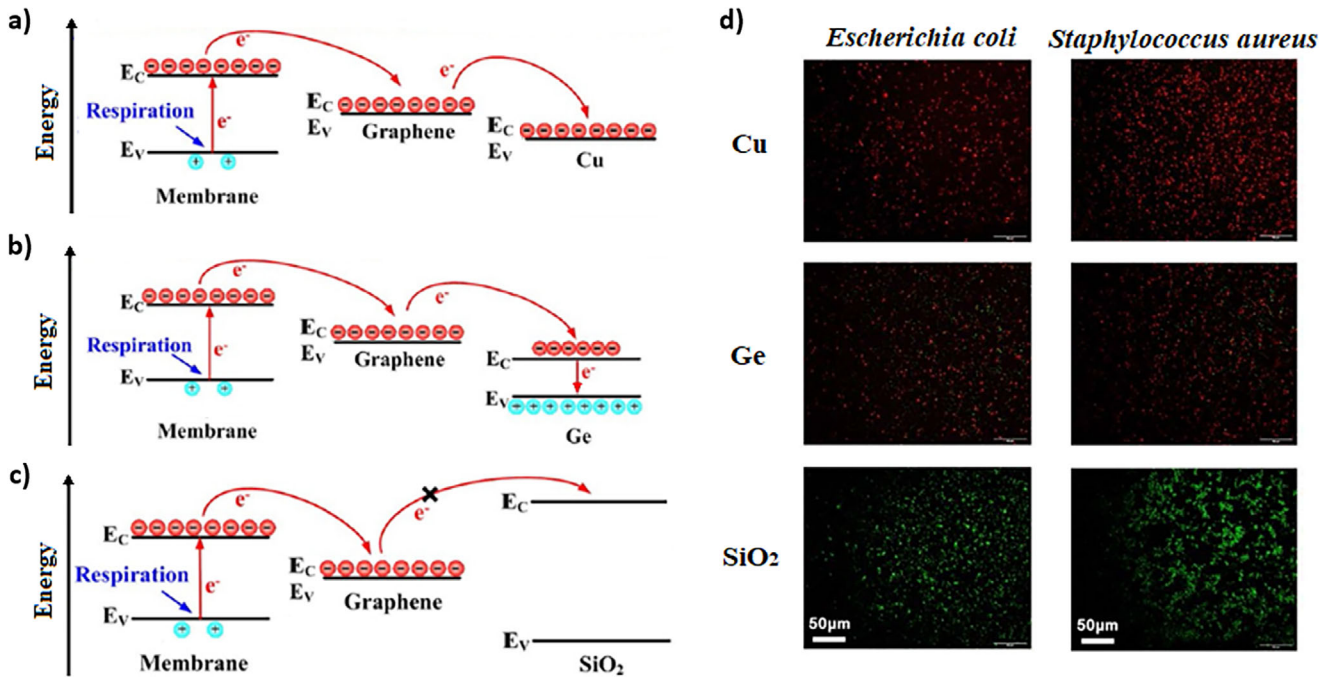

FIGURE 10 | Survival of bacteria on graphene deposited on different substrates. Schematic electronic configuration and electron transport between graphene and (a) conductive copper (Cu), (b) semiconducting germanium (Ge), and (c) insulator silica (SiO_2). (d) Viability of bacteria on graphene deposited in each substrate determined by fluorescence images (red: dead cells, green: live cells). Reproduced with permission [94]. Copyright 2014, Nature.

suppressing bacterial metabolic activity and eliminating the possibility of oxidation induced by the bacteria.

Given that bacterial respiration involves electron transport, the conductivity of the sensing surface is also crucial in developing graphene-based sensors. The good biocompatibility of graphene allows bacteria to come into close proximity with the sensing surface, facilitating interactions not only with the graphene layer but also with its substrate. Additionally, since graphene behaves as a p-type material at room temperature, it acts as an efficient electron acceptor, potentially bridging electron transfer between bacteria and the substrate. Li et al. [94] investigated the responses of two bacterial strains, Gram-negative *E. coli* and Gram-positive *S. aureus*, when exposed to monolayer graphene on substrates with varying electrical conductivities. The substrates studied were conductive copper (Cu), semiconducting germanium (Ge), and insulating silica (SiO_2). It was demonstrated that differences in the electronic band configuration between the bacterial cell wall and the substrate affect bacterial survival on the sensing surface, depending on whether electron transfer is possible, as illustrated in Figure 10. Since the cell wall of both Gram-positive and Gram-negative bacteria can be modeled as a semiconducting material with a significant energy gap between their conductive band (E_C) and valence band (E_V), the differences in E_C between bacteria and each substrate should be analyzed. When the E_C of the substrate is lower than that of the cell wall, electrons from the respiratory process drain into the substrate, as occurs with the conductive Cu and the semiconducting Ge (Figure 10a,b, respectively). In contrast, the conduction band of the insulating SiO_2 substrate has a higher energy than that of the bacterial cell wall, which prevents electron transfer, as represented in Figure 10c. Fluorescence imaging of bacteria on graphene for each substrate, presented in Figure 10d, confirmed that the interruption of electron transport in the respiratory process results in the death of both *E. coli* and *S. aureus* cells. This study highlights the importance of selecting an appropriate substrate for constructing graphene-based bacterial sensors, as it has a significant impact on the biocompatibility of graphene.

4.2.2.4 | Alterations in the Electrical Configuration of Graphene. The substrate selected for the development of graphene-based sensors not only determines the survival of bacteria on the sensing surface but also influences the electrical behavior of the sensor and defines its potential application field. As discussed in the previous section, silica/silicium (SiO_2/Si) is the most commonly used substrate in graphene-based sensor construction. This is due to its strong covalent bonding with graphene, its inertness in altering the electrical behavior of the sensing material, and its suitable properties for building reliable electrical sensors [95]. On the other hand, metal substrates often induce significant changes in the electronic configuration of graphene, leading to the opening of a band gap, which causes a loss of its ambipolarity [96]. Polymer substrates, such as the flexible acetate used by Basu et al. [81], are limited by the interaction strength between the two surfaces, which is mediated by van der Waals forces. The weak bonding allows graphene to retain its intrinsic physicochemical properties [58]. Additionally, polymer substrates enable the fabrication of transparent and flexible devices, which can lead to more efficient sensing technologies since it mold to the sample, providing a larger contact area [97].

It is important to emphasize that the sensitivity of graphene to changes in its electronic behavior can be considered as an advantageous feature for engineering graphene with tailored properties.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Numerous studies have explored various techniques to tune the electronic band structure of graphene [98–100]. These techniques include molecular doping via substitution of carbon atoms or adsorption of molecules, the introduction of defects through electron or ion beam irradiation, hydrogenation, fluorination, and oxidation, and also, substrate selection. A notable example of property tuning was demonstrated by Rao et al. [80], who developed a graphene-based bacterial sensor by cutting a graphene strip to a width comparable to that of bacteria. The authors reported that the semimetal behavior of graphene was lost, and the micro ribbon exhibited semiconductor-like properties. As the size is reduced, graphene turns from a 2D to a 1D material, and its electronic band structure changes by the opening of a bandgap and confinement of charges. Consequently, these changes alter its transport properties, resulting in a sensor with higher sensitivity. Rao et al. [80] also demonstrated that the sensitivity of graphene-based sensors can be improved by controlling the number of carbon layers. Due to interlayer resistances, it was shown that the higher the number of layers, the higher the electrical resistance, until the resistivity of graphite is reached [101]. The obstacles in charge transport, generated by interlayer resistances, result in a reduced sensitivity of the graphene-based sensor as the number of layers increases.

4.2.2.5 | Selection and Configuration of Metal Electrodes. A key factor in developing graphene devices is the contact between graphene and metal electrodes. A complex phenomenon takes place where charge carriers are injected from a 3D metal electrode into the 2D semimetal graphene layer. Due to differences in electronic configuration and dimensions, contact resistance between the two materials is formed, resulting in an energy barrier to charge carrier injection, affecting the performance of the electrical sensor [102]. Low contact resistance in graphene–metal contacts can be observed through the *IV* curve, which will show a linear response, as highlighted by Wibowo et al. [22, 83] for the portable graphene-based sensor they developed. The linear response is characteristic of an ohmic contact, as the *IV* curve follows Ohm's law. Zheng et al. [103] present a review of strategies to form ohmic contacts between 2D materials, such as graphene, and 3D metal electrodes. These strategies, which include doping, energy band matching, and optimizing electrode configuration, aim to enhance the reliability and sensitivity of the conventional method involving metal deposition onto graphene. The performance of electrical graphene-based sensors can also be influenced by the structural orientation of graphene. Rao et al. [80] demonstrated the impact of graphene orientation on sensor sensitivity by comparing the responses of the bare sensor with different electrode pairs. They used a configuration of four electrodes printed onto the graphene sensing surface, where the electrical resistance measured by one pair of electrodes was higher than a different pair of electrodes. Since the electrode area and distance between them are constant, the differences in electrical response between the electrode pairs are attributed to the orientation of graphene. Exploring graphene orientation is crucial when developing electrical sensors since directions that facilitate charge carrier movement are promising for creating devices with higher sensitivity.

4.2.2.6 | Medium and Environmental Conditions. The principle of measurement in the studied graphene-based sensors relies on changes in electrical behavior due to the adsorption of bacteria. Therefore, direct contact with the analyte is required. This type of measurement can perturb the sensing layer due to various factors, such as temperature and composition, where chemical species, ions, and water are of particular interest. These factors are typically influenced by the sample being analyzed, which can have a wide range of characteristics. This is especially true when considering that the target analyte is bacteria, and when the sample is food. Temperature is a key factor to consider, since graphene increases its conductivity with temperature due to a stimulation of the charge carriers [104]. In addition to the surrounding media and sample, the conduction of electricity through graphene can also increase the temperature of the sensor due to the Joule effect, causing it to eventually fail [105]. The composition of the sample involves not only the medium in which the bacteria are present, but also the metabolic byproducts of the bacteria, which vary depending on the growth stage of the cells [106]. This is especially important when bacteria produce biofilms, as they secrete polymeric substances that lead in biofilm formation. The complexity of biofilms requires special attention to ensure the correct interpretation of sensor responses. Nakagawa et al. [84] proposed an electrical model to describe the behavior of their impedimetric graphene-based sensor during biofilm detection. The model accounts for preferential current pathways under different applied frequencies: at high frequencies, the current predominantly flows through regions rich in the polymeric substances of the biofilm, whereas at low frequencies, it tends to pass through the more aqueous areas.

It is important to analyze the effect of ions and water on the composition of the medium because they form an electrolyte that can conduct current and potentially interfere with the sensor response. This is because the electrolyte is not the target analyte. One way to avoid electrolyte interference is to dry the sample before sensing. This can be done by heating, as Rao et al. [80] did with their sensor, or by natural evaporation, as performed by Mulyana et al. [82] and Nakagawa et al. [84]. When measuring in the presence of an electrolyte it is necessary to know its electrical response before including the bacteria to the analysis. [22, 23, 81, 83] An interesting consideration when measuring liquid samples is to prevent evaporation during the time the sensor needs to yield a result. To address this, Daly et al. [79] proposed adding glycerol to the sample, since it is a substance that increases surface tension and reduces evaporation during measurement. Even in the absence of an electrolyte, humidity normally is present in the environment. This is not a minor factor since it was demonstrated by Teoh et al. [107] that the current flow going through graphene can promote its reaction with water molecules of the ambient, conducting to an oxidation or even a reduction of the material. It is important to note that temperature and composition of the sample not only affect the graphene sensing layer but also have a significant impact on the metabolism of bacteria and, consequently, on their adhesion [108].

4.3 | Comparative Analysis and Discussion

Only a few non-functionalized graphene-based electrical sensors have been developed for bacterial detection since 2012. Figure 11 summarizes key information that enables a proper comparison of the electrical response to bacteria adhesion of these sensors,

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

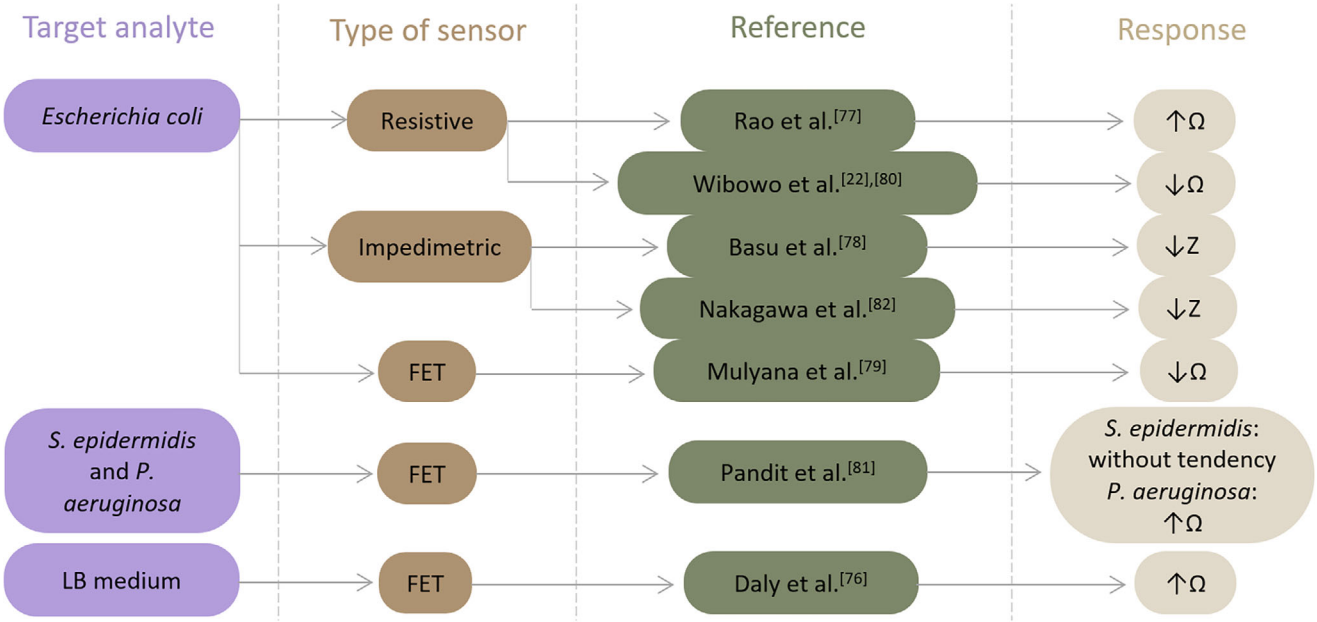

FIGURE 11 | Key information and electrical responses of non-functionalized electrical graphene-based bacterial sensors.

highlighting the impact of the previously described constructive and operational factors on sensor performance.

A comparative analysis can be conducted between the sensor developed by Rao et al. [80] and Wibowo et al. [22, 83] as both are graphene-based resistive sensors designed for detecting *E. coli*. It can be noticed that their responses are opposite: while one sensor exhibits an increase in the electrical resistance in the presence of bacteria, the other one shows a decrease. There are two key factors that may lead to this variation in sensor response: the production method of graphene and the sample conditions. Despite having the same substrate (SiO_2/Si) and electrode configuration, Rao et al. [80] utilized mechanically exfoliated graphene, directly transfer onto the substrate, whereas Wibowo et al. [22, 83] used CVD graphene, which likely required a transfer process to deposit it onto the substrate. Both sensors measured *E. coli* dispersed in DI water; however, Rao et al. [80] dried the bacterial solution before measurement, while Wibowo et al. [22, 83] analyzed a liquid drop of the solution. It is also important to note that both studies implemented a centrifugation step to disperse the bacteria into DI water. This process may be a relevant factor, as centrifugation has been reported to alter the surface charge of bacterial cells [109]. Regarding the number of graphene layers, it appears to affect the sensitivity rather than the direction of the response, since Rao et al. [80] analyzed mono-, bi-, and few-layer graphene, consistently observing an increase in the electrical resistance when *E. coli* gets in touch with the sensor.

Another comparative analysis can be conducted between the sensors developed by Basu et al. [81] and Nakagawa et al. [84] since both are graphene-based impedimetric sensors and the target analyte is *E. coli*. Despite exhibiting the same response, which is a decrease in impedance with bacteria adhesion, there are significant differences between them, including the substrate, electrode configuration, and sample conditions. Both sensors utilized CVD graphene; however, Basu et al. [81] employed a SiO_2/Si substrate, while Nakagawa et al. [84] used a Cu substrate. In this last device, no transfer method was required as CVD graphene was directly grown on Cu, whereas the other sensor required a transfer method. Moreover, there is a significant difference in electrode configuration that determines the direction of the current path in each sensor. In the device developed by Basu et al. [81] the electrical current flows exclusively through graphene, parallel to the sensing surface. Conversely, in the sensor constructed by Nakagawa et al. [84], the current flows through both graphene and the Cu substrate, in a direction perpendicular to the sensing surface. Regarding sample conditions, both sensors measured *E. coli* dispersed in LB medium. However, Basu et al. [81] analyzed a liquid drop, while Nakagawa et al. [84] dried the sample prior to measurement. Since the bacteria were suspended in their growth medium, no centrifugation step was required in either study. It is interesting to note that Nakagawa et al. [84] investigated the response of the sensor to the biofilm formation. In this case, the sensor response shifted, showing an increase in impedance due to the presence of bacteria and biofilm. This highlights the importance of studying the influence of bacterial metabolism byproducts on sensor response.

This comparative analysis suggests that the graphene production method has the most significant influence on sensor performance. Additionally, bacterial metabolic byproducts appear to play a crucial role in sensor response. This is supported by the FET graphene-based sensor developed by Pandit et al. [23] that monitored the electrical resistance while bacteria grew in culture mediums under favorable conditions. Among the two bacteria tested, *P. aeruginosa* exhibited a linear response in which the electrical resistance increased with bacterial adhesion, whereas *S. epidermidis* showed a non-linear response, indicating the impact of metabolic byproducts and biofilm formation.

The studies conducted by Mulyana et al. [82] provided valuable insights, as they reported a decrease in electrical resistance when bacteria adhered to the graphene sensing layer. Moreover, an increase in the electrical resistance indicated that chemical

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

reactions, such as oxidation of graphene, occurred during measurement. Given that both bacteria and electrical current can induce graphene oxidation, it is crucial to determine whether physical or chemical interactions are taking place between graphene and bacteria. The findings from existing studies highlight the need for deeper investigation and testing to fully understand how constructive and operational parameters influence the performance of non-functionalized electrical graphene-based bacterial sensors.

4.4 | Main Challenges

The development of an ideal bacterial sensor requires particular attention to factors such as sensitivity, selectivity, and physicochemical stability. Although functionalized bacterial sensors meet essential criteria such as speed, cost-effectiveness, portability, and ease of use, non-functionalized sensors still face other critical challenges in practical application. Sensitivity is especially critical for food samples, where the acceptable limit for some pathogenic bacteria is just a few cells per 100 mL [110]. Current bacterial detection technologies typically have a volumetric capacity of only a few milliliters, and further advancements are needed to achieve higher capacity and sensitivity without relying on preprocessing steps for sample concentration that are time and cost-intensive [78]. Some approaches have been explored, such as integrating microfluidic structures into biosensors to enable real-time sample concentration. However, these structures present operational challenges, such as the risk of damaging the sample, which compromises the device's reliability [111]. As demonstrated by Rao et al. [80], non-functionalized graphene-based sensors can achieve single-cell detection; however, this level of performance can decrease significantly when the sensor is exposed to real, complex matrices, such as food. Selectivity remains one of the major challenges for bacterial sensors, particularly non-functionalized ones. Unlike functionalized devices, such as biosensors that depend strictly on specific biorecognition elements, non-functionalized sensors detect bacteria through direct, intrinsic interactions between the target microorganism and the sensing surface. This raises concerns about their ability to distinguish between different bacterial species or to discriminate bacteria from other biological or chemical components in the sample. Interestingly, the graphene-based sensor developed by Pandit et al. [23] exhibited differential responses to distinct bacterial strains, which may be related to differences in cell wall composition or metabolic activity. As a result, it is intriguing to consider whether graphene can directly detect differences in cells and respond accordingly due to its electrical properties. While graphene's high sensitivity can be advantageous for detection, it also makes the sensing layer susceptible to non-target stimuli, such as humidity, oxygen, and temperature, which can alter its electronic behavior. These fluctuations contribute to the inherent instability of graphene and may compromise the reliability of sensors, particularly in complex matrices like food. A stable sensing layer is a key factor to enable sensor reuse and regeneration processes, and, consequently, ensuring the long-term durability of devices [112]. Together, sensitivity, selectivity, and physicochemical stability, along with key attributes such as speed, affordability, ease of use, and portability define the essential features of a reliable, non-functionalized bacterial sensor. Meeting these criteria is crucial for the successful development of practical devices with strong potential for real-world applications and future market integration.

5 | Concluding Remarks

Graphene exhibits unique physical and chemical properties that make it a promising material for the development of non-functionalized bacterial sensors. Its high surface area and 2D structure enable strong interactions with analytes, while its compatibility with living cells allows for the direct adsorption of bacteria. Particularly, its electronic characteristics make graphene ideal for developing electrical sensors. Its excellent charge carrier mobility, combined with its intrinsic ambipolarity that allows it to conduct electricity through electrons and holes, ensures the creation of versatile sensing devices with tunable characteristics.

A wide range of graphene quality and form is available not only because of its electronic properties, but also because it can be produced using various techniques classified as either bottom–up or top–down. While this variety poses challenges due to the lack of uniform quality control protocols, it also enables the selection of graphene with the most suitable properties for sensor optimization. Another significant advantage of using graphene in sensor development is its affinity with various substrates, including metals, ceramics, and polymers. This offers considerable versatility in sensor design, particularly for the development of portable sensors that can support decentralized, low-cost monitoring in rural or resource-limited settings. Additionally, using flexible substrates enables the fabrication of bendable sensors that can be integrated into systems such as packaging. This application is especially relevant for detecting foodborne bacteria through intelligent food packaging solutions.

The high sensitivity of graphene to external factors such as temperature, chemical species, living cells, and electrical or magnetic fields allows for the construction of sensitive and highly reliable sensors. Graphene-based field-effect transistor sensors are a promising configuration for bacterial detection and allow us to fully exploit graphene's electronic properties. These devices modulate the charge carrier density on graphene, providing greater control over device operation, which is crucial when dealing with samples containing living cells that often yield dynamic responses. Furthermore, this review discusses how graphene-based sensors emerged to overcome the limitations of conventional bacterial detection methods and biosensors. Traditional approaches, such as culturing, biochemical assays, nucleic acid sequence-based detection, and immunological detection, provide high sensitivity and selectivity, but they often require long processing times, expensive reagents, complex preprocessing, and trained personnel. Meanwhile, biosensors are compact, portable devices that provide a fast response; however, they are limited in terms of sensitivity and scalability. Non-functionalized graphene sensors are an innovative alternative offering fast, cost-effective, on-site detection. They are simple and easy to use, making them particularly suitable for scalable real-world applications, such as food safety monitoring, where fast, affordable, and user-friendly solutions are crucial.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

This review highlights the key findings from studies on non-functionalized electrical graphene-based bacterial sensors, emphasizing both their potential and the challenges that remain. The reviewed sensor types include resistive, impedimetric, and FET-based sensors. Significant advances have been made in demonstrating the capability of graphene to directly sense bacteria without the need for intermediate agents. Moreover, graphene has shown the ability to tune sensitivity simply by controlling parameters such as thickness and shape, achieving detection limits as low as a single bacterial cell. Additionally, graphene-based sensors exhibit differential responses to different bacteria species, highlighting their promising selectivity. These sensors have successfully sensed both wet and dried samples, proving their versatility. It has been demonstrated that a deeper understanding and exploitation of the distinctive electrical properties of graphene can enable reliable bacterial detection, promising for sensing complex media such as food samples. Beyond detecting bacterial cells, graphene has also shown the ability to sense biofilm formation, expanding its potential, for example, to the healthcare field. Furthermore, the discussed graphene-based sensors have been developed with flexible, real-time monitoring, or portable designs, enhancing their practical usability. Even though no studies have yet explored the regeneration and reuse of these sensors, the fact that bacterial interaction with graphene occurs primarily through physical adsorption suggests promising potential for sensor reutilization. Moreover, this review identifies critical constructive and operational factors that directly impact on sensor performance. One of the most important factors is the molecular structure and composition of graphene, as it has a significant influence on its electronic behavior, and consequently, on sensor response. This molecular structure can be altered primarily by the production process of graphene and the transfer or deposition method used to construct the sensor. Additionally, the materials selected for the substrate and electrode can also affect the electronic configuration of graphene. More importantly, these materials influence bacterial metabolism, which directly impacts on bacterial adhesion. Determining the physical or chemical interactions that occur during the sensing process is challenging because they are driven not only by graphene–analyte interaction but also by the flow of electrical current.

Despite the significant potential of non-functionalized electrical graphene-based bacterial sensors, several critical challenges must be addressed to achieve reliable and scalable devices. Ensuring sensitivity, selectivity, and physicochemical stability is essential for real-world applications. The absence of biorecognition elements hinders selective detection, and the high sensitivity of graphene makes it susceptible to interference from environmental factors. Furthermore, ensuring long-term operational stability and developing reusable devices remain unresolved issues. Overcoming these challenges requires strong interdisciplinary efforts, integrating advances from materials science, microbiology, and electronic engineering. Closer collaboration between academic research and industrial development is also crucial to translating laboratory findings into practical, market-ready technologies.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. M. Taghioskoui, "Trends in graphene research," *Materials Today* 12, no. 10 (2009): 34–37.

2. R. Ma, Y. Zhou, H. Bi, et al., "Multidimensional Graphene Structures and Beyond: Unique Properties, Syntheses and Applications," *Progress in Materials Science* 113 (2020): 100665.

3. R. Urcuyo, D. González-Flores, and K. Cordero-Solano, "Perspectivas e Aplicações Reais Do Grafeno Após 16 Anos de Sua descoberta Introducción," *Revista Colombiana De Química* 50, no. 1 (2020): 51–85.

4. P. C. Henriques, A. T. Pereira, A. L. Pires, A. M. Pereira, F. D. Magalhães, and I. C. Gonçalves, "Graphene Surfaces Interaction With Proteins, Bacteria, Mammalian Cells, and Blood Constituents: The Impact of Graphene Platelet Oxidation and Thickness," *ACS Applied Materials and Interfaces* 12, no. 18 (2020): 21020–21035.

5. S. Ren, P. Rong, and Q. Yu, "Preparations, Properties and Applications of Graphene in Functional Devices: A Concise Review," *Ceramics International* 44, no. 11 (2018): 11940–11955.

6. P. Dave and A. Rajani, "Review on Carbon-Graphene Nanocomposite Based Conductive-Ink in Printed Electronics," *Int J Adv Nano Comput Anal* 1, no. 1 (2021): 61–83.

7. A. G. Olabi, M. A. Abdelkareem, T. Wilberforce, and E. T. Sayed, "Application of graphene in energy storage device—A review," *Renewable and Sustainable Energy Reviews* 135 (2021): 110026.

8. Y. Jia, J. Zhang, D. Kong, et al., "Practical Graphene Technologies for Electrochemical Energy Storage," *Advanced Functional Materials* 32 (2022): 2204272.

9. T. P. Dasari Shareena, D. McShan, A. K. Dasmahapatra, and P. B. Tchounwou, "A Review on Graphene-Based Nanomaterials in Biomedical Applications and Risks in Environment and Health," *Nano-Micro Letters* 10, no. 3 (2018): 1–34.

10. Y. Fang and E. Wang, "Electrochemical Biosensors on Platforms of Graphene," *Chemical Communications* 49, no. 83 (2013): 9526–9539.

11. A. Chaudhari, P. Jagdale, P. Goswami, and M. A. K. Kerawalla, "Recent Advancements in Graphene Biosensors for the Detection of Pathogens—A Review," *Indian Drugs* 55, no. 8 (2018): 7–17.

12. J. Peña-Bahamonde, H. N. Nguyen, S. K. Fanourakis, and D. F. Rodrigues, "Recent Advances in Graphene-based Biosensor Technology With Applications in Life Sciences," *Journal of Nanobiotechnology* 16, no. 1 (2018): 1–17.

13. S. M. Pires, B. N. Desta, L. Mughini-Gras, et al., "Burden of Foodborne Diseases: Think Global, Act Local," *Current Opinion in Food Science* 39 (2021): 152–159.

14. J. Riu and B. Giussani, "Electrochemical Biosensors for the Detection of Pathogenic Bacteria in Food," *TrAC—Trends in Analytical Chemistry* 126 (2020): 115863.

15. S. Galié, C. García-Gutiérrez, E. M. Miguélez, C. J. Villar, and F. Lombó, "Biofilms in the Food Industry: Health Aspects and Control Methods," *Frontiers in Microbiology* 9 (2018): 1–18.

16. L. Xu, X. Bai, and A. K. Bhunia, "Current state of Development of Biosensors and Their Application in Foodborne Pathogen Detection," *Journal of Food Protection* 84, no. 7 (2021): 1213–1227.

17. J. Gao, A. Chakraborthy, S. He, et al., "Graphene-Based Sensors for the Detection of Microorganisms in Food: A Review," *Biosensors* 13, no. 6 (2023): 1–14.

18. K. S. Jaiswal, N. N. Kadamannil, and R. Jelinek, "Carbon Nanomaterials in Microbial Sensing and Bactericidal Applications," *Current Opinion in Colloid and Interface Science* 66 (2023): 101719.

19. A. Nag, A. Mitra, and S. Chandra, "Graphene and Its Sensor-based Applications: A Review," *Sensors and Actuators A: Physical* 270 (2018): 177–194.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

20. Z. Jiang, B. Feng, J. Xu, T. Qing, P. Zhang, and Z. Qing, "Graphene Biosensors for Bacterial and Viral Pathogens," *Biosensors and Bioelectronics* 166 (2020): 112471.

21. R. S. Tade, S. N. Nangare, and P. O. Patil, "Fundamental Aspects of Graphene and Its Biosensing Applications," *Functional Composites and Structures* 3, no. 1 (2021): 012001.

22. K. M. Wibowo, A. Muslihati, M. Z. Sahdan, N. M. Rosni, H. Basri, and A. Fudholi, "A Novel, Portable Escherichia coli Bacteria Sensor Using Graphene as Sensing Material," *Materials Chemistry and Physics* 254 (2020): 123459.

23. S. Pandit, M. Li, Y. Chen, et al., "Graphene-based Sensor for Detection of Bacterial Pathogens," *Sensors* 21, no. 23 (2021): 8085.

24. Z. Zhen and H. Zhu, "Structure and Properties of graphene," *Graphene* (Academic Press, 2018): 1–12.

25. ISO/TS 80004–13:2017, Nanotechnologies—Vocabulary—Part 13: Graphene and Related Two-Dimensional, 2D) Materials. ISO, 2017, https://www.iso.org/standard/64741.html, accessed: 2017.

26. Y. Nagai, H. Sugime, and S. Noda, "1.5 Min-synthesis of Continuous Graphene Films by Chemical Vapor Deposition on Cu Foils Rolled in Three Dimensions," *Chemical Engineering Science* 201 (2019): 319–324.

27. C. F. P. Kastorp, D. A. Duncan, M. Scheffler, et al., "Growth and Electronic Properties of bi- And Trilayer Graphene on Ir(111)," *Nanoscale* 12, no. 38 (2020): 19776–19786.

28. S. J. Rowley-Neale, E. P. Randviir, A. S. Abo Dena, and C. E. Banks, "An Overview of Recent Applications of Reduced Graphene Oxide as a Basis of Electroanalytical Sensing Platforms," *Applied Materials Today* 10 (2018): 218–226.

29. W. Yu, L. Sisi, Y. Haiyan, and L. Jie, "Progress in the Functional Modification of Graphene/Graphene Oxide: A Review," *RSC Advances* 10, no. 26 (2020): 15328–15345.

30. P. Feicht and S. Eigler, "Defects in Graphene Oxide as Structural Motifs," *ChemNanoMat* 4, no. 3 (2018): 244–252.

31. M. Sieradzka, C. Ślusarczyk, W. Biniaś, and R. Fryczkowski, "The Role of the Oxidation and Reduction Parameters on the Properties of the Reduced Graphene Oxide," *Coatings* 11, no. 2 (2021): 166.

32. L. Torrisi, M. Cutroneo, A. Torrisi, and L. Silipigni, "Measurements on Five Characterizing Properties of Graphene Oxide and Reduced Graphene Oxide Foils," *(Physica Status Solidi, A) Applications and Materials Science* 219, no. 6 (2022): 2100628.

33. F. Zhang, K. Yang, G. Liu, et al., "Recent Advances on Graphene: Synthesis, Properties and Applications," *Composites Part A: Applied Science and Manufacturing* 160 (2022): 107051.

34. X. L. Wang, S. X. Dou, and C. Zhang, "Zero-gap Materials for Future Spintronics, Electronics and Optics," *NPG Asia Materials* 2, no. 1 (2010): 31–38.

35. F. Pasadas, A. Medina-Rull, F. G. Ruiz, et al., "Exploiting Ambipolarity in Graphene Field-Effect Transistors for Novel Designs on High-Frequency Analog Electronics," *Small* 19, no. 49 (2023): 2303595.

36. X. Wang, Y. Chen, G. Wu, et al., "Graphene Dirac Point Tuned by Ferroelectric Polarization Field," *Nanotechnology* 29, no. 13 (2018): 134002.

37. E. Piccinini, C. Bliem, J. M. Giussi, W. Knoll, and O. Azzaroni, "Reversible Switching of the Dirac Point in Graphene Field-Effect Transistors Functionalized With Responsive Polymer Brushes," *Langmuir* 35, no. 24 (2019): 8038–8044.

38. D. S. Sutar, G. Singh, and V. Divakar Botcha, "Electronic Structure of Graphene Oxide and Reduced Graphene Oxide Monolayers," *Applied Physics Letters* 101, no. 10 (2012): 103103.

39. Z. Zhang, A. Fraser, S. Ye, G. Merle, and J. Barralet, "Top-Down Bottom-up Graphene Synthesis," *Nano Futures* 3, no. 4 (2019): 042003.

40. R. Ye and J. M. Tour, "Graphene at fifteen," *ACS Nano* 13, no. 10 (2019): 10872–10878.

41. L. Yang, W. Chen, Q. Yu, and B. Liu, "Mass Production of Two-dimensional Materials Beyond Graphene and Their Applications," *Nano Research* 14, no. 6 (2021): 1583–1597.

42. Y. Yan, F. Z. Nashath, S. Chen, et al., "Synthesis of Graphene: Potential Carbon Precursors and Approaches," *Nanotechnology Reviews* 9, no. 1 (2020): 1284–1314.

43. H. C. Lee, W.-W. Liu, S.-P. Chai, et al., "Review of the Synthesis, Transfer, Characterization and Growth Mechanisms of Single and Multilayer Graphene," *RSC Advances* 7, no. 26 (2017): 15644–15693.

44. A. T. Smith, A. M. LaChance, S. Zeng, B. Liu, and L. Sun, "Synthesis, Properties, and Applications of Graphene Oxide/Reduced Graphene Oxide and Their Nanocomposites," *Nano Materials Science* 1, no. 1 (2019): 31–47.

45. F. Farjadian, S. Abbaspour, M. A. A. Sadatlu, et al., "Recent Developments in Graphene and Graphene Oxide: Properties, Synthesis, and Modifications: A Review," *ChemistrySelect* 5, no. 33 (2020): 10200–10219.

46. R. Tarcan, O. Todor-Boer, I. Petrovai, C. Leordean, S. Astilean, and I. Botiz, "Reduced Graphene Oxide Today," *Journal of Materials Chemistry C* 8, no. 4 (2020): 1198–1224.

47. L. Gan, B. Li, Y. Chen, B. Yu, and Z. Chen, "Green Synthesis of Reduced Graphene Oxide Using Bagasse and Its Application in Dye Removal: A Waste-to-resource Supply Chain," *Chemosphere* 219 (2019): 148–154.

48. A. P. Kauling, A. T. Seefeldt, D. P. Pisoni, et al., "The Worldwide Graphene Flake Production," *Advanced Materials* 30, no. 44 (2018): 1–6.

49. V. Kumar, A. Kumar, D. J. Lee, and S. S. Park, "Estimation of Number of Graphene Layers Using Different Methods: A Focused Review," *Materials* 14, no. 16 (2021): 4590.

50. R. Muzyka, S. Drewniak, T. Pustelny, M. Chrubasik, and G. Gryglewicz, "Characterization of Graphite Oxide and Reduced Graphene Oxide Obtained From Different Graphite Precursors and Oxidized by Different Methods Using Raman Spectroscopy," *Materials* 11, no. 7 (2018): 15–17.

51. A. Kovtun, D. Jones, S. Dell'Elce, E. Treossi, A. Liscio, and V. Palermo, "Accurate Chemical Analysis of Oxygenated Graphene-based Materials Using X-ray Photoelectron Spectroscopy," *Carbon* 143 (2019): 268–275.

52. A. L. Olatomiwa, T. Adam, S. C. B. Gopinath, S. Y. Kolawole, O. H. Olayinka, and U. Hashim, "Graphene Synthesis, Fabrication, Characterization Based on Bottom-up and Top-Down Approaches: An Overview," *Journal of Semiconductors* 43, no. 6 (2022): 061101.

53. M. Saeed, Y. Alshammari, S. A. Majeed, and E. Al-Nasrallah, "Chemical Vapour Deposition of Graphene—Synthesis, Characterization, and Applications: A Review," *Molecules* 25, no. 17 (2020): 3856.

54. M. A. Yoon, C. Kim, J. H. Kim, H. J. Lee, and K. S. Kim, "Surface Properties of CVD-grown Graphene Transferred by Wet and Dry Transfer Processes," *Sensors* 22, no. 10 (2022): 3944.

55. K. Zhang, J. Hart, and A. J. Hart, "Interfacial Chemical Vapor Deposition of Wrinkle-free Bilayer Graphene on Dielectric Substrates," *Applied Surface Science* 602 (2022): 154367.

56. K. Shrivas, A. Ghosale, P. K. Bajpai, T. Kant, K. Dewangan, and R. Shankar, "Advances in Flexible Electronics and Electrochemical Sensors Using Conducting Nanomaterials: A Review," *Microchemical Journal* 156 (2020): 104944.

57. T. S. Tran, N. K. Dutta, and N. R. Choudhury, "Graphene Inks for Printed Flexible Electronics: Graphene Dispersions, Ink Formulations, Printing Techniques and Applications," *Advances in Colloid and Interface Science* 261 (2018): 41–61.

58. G. Zhao, X. Li, M. Huang, et al., "The Physics and Chemistry of Graphene-on-surfaces," *Chemical Society Reviews* 46, no. 15 (2017): 4417–4449.

59. P. F. M. Pereira, P. H. de Sousa Picciani, V. Calado, and R. V. Tonon, "Electrical Gas Sensors for Meat Freshness Assessment and Quality

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Monitoring: A Review," *Trends in Food Science and Technology* 118 (2021): 36–44.

60. E. Fazio, S. Spadaro, C. Corsaro, et al., "Metal-oxide Based Nanomaterials: Synthesis, Characterization and Their Applications in Electrical and Electrochemical Sensors," *Sensors* 21, no. 7 (2021): 2494.

61. P. Gründler, "Conductivity Sensors and Capacitive Sensors," *Chemical Sensors: An Introduction for Scientist and Engineersn Introduction for Scientist and Engineers* (Springer, 2007): 123–132.

62. J. Janata, "Conductometric sensors," *Principles of Chemical Sensors* (Springer, 2009): 241–266.

63. Y. Singh, "Electrical Resistivity Measurements: A Review," *International Journal of Modern Physics: Conference Series* 22 (2013): 745–756.

64. S. He, Y. Yuan, A. Nag, et al., "A Review on the Use of Impedimetric Sensors for the Inspection of Food Quality," *International Journal of Environmental Research and Public Health* 17, no. 14 (2020): 1–30.

65. D. Reddy, L. F. Register, G. D. Carpenter, and S. K. Banerjee, "Graphene Field-effect Transistors," *Journal of Physics D: Applied Physics* 44, no. 31 (2011): 313001.

66. S. Mao, "Graphene Field-Effect Transistor Sensors," *Graphene Bioelectronics* (Tongji University, 2018): 113–132.

67. T. Kuila, S. Bose, P. Khanra, A. K. Mishra, N. H. Kim, and J. H. Lee, "Recent Advances in Graphene-based Biosensors," *Biosensors and Bioelectronics* 26, no. 12 (2011): 4637–4648.

68. W. Fu, L. Jiang, E. P. van Geest, L. M. C. Lima, and G. F. Schneider, "Sensing at the Surface of Graphene Field-Effect Transistors," *Advanced Materials* 29, no. 6 (2017): 1–25.

69. S. Chen, Y. Sun, X. Fan, et al., "Review on Two-dimensional Material-based Field-effect Transistor Biosensors: Accomplishments, Mechanisms, and Perspectives," *Journal of Nanobiotechnology* 21, no. 1 (2023): 1–32.

70. T. Ono, S. Okuda, S. Ushiba, Y. Kanai, and K. Matsumoto, "Challenges for Field-Effect-Transistor-Based Graphene Biosensors," *Materials* 17, no. 2 (2024): 333.

71. V. R. Samuel and K. J. Rao, "A Review on Label Free Biosensors," *Biosensors and Bioelectronics: X* 11 (2022): 100216.

72. T. Zhang and P. L. Tremblay, "Graphene: An Antibacterial Agent or a Promoter of Bacterial Proliferation?," *Iscience* 23, no. 12 (2020): 101787.

73. M. P. Kabiraz, P. R. Majumdar, M. M. C. Mahmud, S. Bhowmik, and A. Ali, "Conventional and Advanced Detection Techniques of Foodborne Pathogens: A Comprehensive Review," *Heliyon* 9, no. 4 (2023): 15482.

74. S. Hameed, L. Xie, and Y. Ying, "Conventional and Emerging Detection Techniques for Pathogenic Bacteria in Food Science: A Review," *Trends in Food Science and Technology* 81 (2018): 61–73.

75. S. C. B. Gopinath, T. H. Tang, Y. Chen, M. Citartan, and T. Lakshmipriya, "Bacterial Detection: From Microscope to Smartphone," *Biosensors and Bioelectronics* 60 (2014): 332–342.

76. A. Canciu, M. Tertis, O. Hosu, A. Cernat, C. Cristea, and F. Graur, "Modern Analytical Techniques for Detection of Bacteria in Surface and Wastewaters," *Sustainability* 13, no. 13 (2021): 1–25.

77. J. Vidic, M. Manzano, C. M. Chang, and N. Jaffrezic-Renault, "Advanced Biosensors for Detection of Pathogens Related to Livestock and Poultry," *Veterinary Research* 48, no. 1 (2017): 1–22.

78. J. J. Ezenarro, J. Mas, X. Muñoz-Berbel, and N. Uria, "Advances in Bacterial Concentration Methods and Their Integration in Portable Detection Platforms: A Review," *Analytica Chimica Acta* 1209 (2022): 339079.

79. R. Daly, S. Kumar, G. Lukacs, et al., "Cell Proliferation Tracking Using Graphene Sensor Arrays," *Journal of Sensors* 2012 (2012): 1–7.

80. F. Rao, H. Al-Mumen, D. Ramos-Gonzalez, L. Dong, and W. Li, "Single-Bacterium Resolution Biosensors Based on Pristine Graphenes," *2012 Int. Conf. Manipulation, Manufacturing and Measurement on the Nanoscale, 3M-NANO 2012 – Conference Proceedings*, (IEEE, 2012), 180–183.

81. P. K. Basu, D. Indukuri, S. Keshavan, et al., "Graphene Based E. coli Sensor on Flexible Acetate Sheet," *Sensors and Actuators B: Chemical* 190 (2014): 342–347.

82. Y. Mulyana, M. Uenuma, N. Okamoto, Y. Ishikawa, I. Yamashita, and Y. Uraoka, "Alterations in Ambipolar Characteristic of Graphene Due to Adsorption of Escherichia coli Bacteria," *Journal of Physics D: Applied Physics* 51, no. 11 (2018): 115102.

83. K. M. Wibowo, M. Z. Sahdan, N. I. Ramli, et al., "Detection of Escherichia Coli Bacteria in Wastewater by Using Graphene as a Sensing Material," *Journal of Physics: Conference Series* 995, no. 1 (2018): 012063.

84. R. Nakagawa, K. Saito, H. Kanematsu, et al., "Impedance Characteristics of Monolayer and Bilayer Graphene Films With Biofilm Formation and Growth," *Sensors* 22, no. 9 (2022): 3548.

85. S. Zheng, M. Bawazir, A. Dhall, et al., "Implication of Surface Properties, Bacterial Motility, and Hydrodynamic Conditions on Bacterial Surface Sensing and Their Initial Adhesion," *Frontiers in Bioengineering and Biotechnology* 9 (2021): 643722.

86. D. P. Linklater, V. A. Baulin, S. Juodkazis, and E. P. Ivanova, "Mechano-bactericidal Mechanism of Graphene Nanomaterials," *Interface Focus* 8, no. 3 (2018): 1–9.

87. H. Gu, A. Chen, X. Song, M. E. Brasch, J. H. Henderson, and D. Ren, "How Escherichia coli Lands and Forms Cell Clusters on a Surface: A New Role of Surface Topography," *Scientific Reports* 6 (2016): 1–14.

88. S. Kreve and A. C. D. Reis, "Bacterial Adhesion to Biomaterials: What Regulates this Attachment? A review," *Japanese Dental Science Review* 57 (2021): 85–96.

89. X. Tang, M. Debliquy, D. Lahem, Y. Yan, and J. P. Raskin, "A Review on Functionalized Graphene Sensors for Detection of Ammonia," *Sensors* 21, no. 4 (2021): 1–28.

90. G. Unden, P. A. Steinmetz, and P. Degreif-Dünnwald, "The Aerobic and Anaerobic Respiratory Chain of Escherichia coli and Salmonella Enterica: Enzymes and Energetics," *EcoSal Plus* 6, no. 1 (2014): 10–1128.

91. E. C. Salas, Z. Sun, A. Lüttge, and J. M. Tour, "Reduction of Graphene Oxide via Bacterial Respiration," *ACS Nano* 4, no. 8 (2010): 4852–4856.

92. O. Akhavan and E. Ghaderi, "Escherichia coli Bacteria Reduce Graphene Oxide to Bactericidal Graphene in a Self-limiting Manner," *Carbon* 50, no. 5 (2012): 1853–1860.

93. G. Utkan, G. Yumusak, B. C. Tunali, T. Ozturk, and M. Turk, "Production of Reduced Graphene Oxide by Using Three Different Microorganisms and Investigation of Their Cell Interactions," *ACS Omega* 8, no. 34 (2023): 31188–31200.

94. J. Li, G. Wang, H. Zhu, et al., "Antibacterial Activity of Large-area Monolayer Graphene Film Manipulated by Charge Transfer," *Scientific Reports* 4 (2014): 4359.

95. A. Walcarius, "Silica-based Electrochemical Sensors and Biosensors: Recent Trends," *Current Opinion in Electrochemistry* 10 (2018): 88–97.

96. E. N. Voloshina and Y. S. Dedkov, "General Approach to Understanding the Electronic Structure of Graphene on Metals," *Materials Research Express* 1, no. 3 (2014): 035603.

97. M. Xu, D. Obodo, and V. K. Yadavalli, "The Design, Fabrication, and Applications of Flexible Biosensing Devices," *Biosensors and Bioelectronics* 124–125 (2019): 96–114.

98. D. Zhan, J. Yan, L. Lai, Z. Ni, L. Liu, and Z. Shen, "Engineering the Electronic Structure of Graphene," *Advanced Materials* 24, no. 30 (2012): 4055–4069.

99. X. Xu, C. Liu, Z. Sun, et al., "Interfacial Engineering in Graphene Bandgap," *Chemical Society Reviews* 47, no. 9 (2018): 3059–3099.

100. R. Nandee, M. A. Chowdhury, A. Shahid, N. Hossain, and M. Rana, "Band Gap Formation of 2D Materialin Graphene: Future Prospect and Challenges," *Results in Engineering* 15 (2022): 100474.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by CochraneItalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

101. P. N. Nirmalraj, T. Lutz, S. Kumar, G. S. Duesberg, and J. J. Boland, "Nanoscale Mapping of Electrical Resistivity and Connectivity in Graphene Strips and Networks," *Nano Letters* 11, no. 1 (2011): 16–22.

102. F. Giubileo and A. Di Bartolomeo, "The Role of Contact Resistance in Graphene Field-effect Devices," *Progress in Surface Science* 92, no. 3 (2017): 143–175.

103. Y. Zheng, J. Gao, C. Han, and W. Chen, "Ohmic Contact Engineering for Two-Dimensional Materials," *Cell Reports Physical Science* 2, no. 1 (2021): 100298.

104. S. Sibilia, F. Bertocchi, S. Chiodini, et al., "Temperature-dependent Electrical Resistivity of Macroscopic Graphene Nanoplatelet Strips," *Nanotechnology* 32, no. 27 (2021): 275701.

105. H. Al-Mumen, F. Rao, L. Dong, and W. Li, "Design, Fabrication, and Characterization of Graphene Thermistor," *8th Annual IEEE Int. Conf. Nano/Micro Engineered and Molecular Systems*, *IEEE NEMS 2013*, (IEEE, 2013), 1135–1138.

106. R. Le Borgne, "The Release of Soluble End Products of metabolism," *The Biological Chemistry of Marine Copepods* (Oxford University Press, 1986): 109–164.

107. H. F. Teoh, Y. Tao, E. S. Tok, G. W. Ho, and C. H. Sow, "Electrical Current Mediated Interconversion Between Graphene Oxide to Reduced Grapene Oxide," *Applied Physics Letters* 98, no. 17 (2011): 2011–2014.

108. A. E. Zeraik and M. Nitschke, "Influence of Growth media and Temperature on Bacterial Adhesion to Polystyrene Surfaces," *Brazilian Archives of Biology and Technology* 55, no. 4 (2012): 569–576.

109. S. S. Tazehkand, S. Torkzaban, S. A. Bradford, and S. L. Walker, "Cell Preparation Methods Influence Escherichia coli D21G Surface Chemistry and Transport in Saturated Sand," *Journal of Environmental Quality* 37, no. 6 (2008): 2108–2115.

110. S. T. Odonkor and T. Mahami, "Escherichia coli as a Tool for Disease Risk Assessment of Drinking Water Sources," *International Journal of Microbiology* (2020): 1–7.

111. M. A. Buttkewitz, C. Heuer, and J. Bahnemann, "Sensor Integration Into Microfluidic Systems: Trends and Challenges," *Current Opinion in Biotechnology* 83 (2023): 102978.

112. A. Ahmed, J. V. Rushworth, N. A. Hirst, and P. A. Millner, "Biosensors for Whole-cell Bacterial Detection," *Clinical Microbiology Reviews* 27, no. 3 (2014): 631–646.

21967350, 0, Downloaded from https://advanced.onlinelibrary.wiley.com/doi/10.1002/admi.202500758 by Cochraneltalia, Wiley Online Library on [25/02/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License