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Review

Antimicrobial Activities of Conducting Polymers and Their Composites

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Abstract: Conducting polymers, mainly polyaniline (PANI) and polypyrrole (PPY) with positive charges bind to the negatively charged bacterial membrane to interfere with bacterial activities. After this initial electrostatic adherence, the conducting polymers might partially penetrate the bacterial membrane and interact with other intracellular biomolecules. Conducting polymers can form polymer composites with metal, metal oxides, and nanoscale carbon materials as a new class of antimicrobial agents with enhanced antimicrobial properties. The accumulation of elevated oxygen reactive species (ROS) from composites of polymers-metal nanoparticles has harmful effects and induces cell death. Among such ROS, the hydroxyl radical with one unpaired electron in the structure is most effective as it can oxidize any bacterial biomolecules, leading to cell death. Future endeavors should focus on the combination of conducting polymers and their composites with antibiotics, small peptides, and natural molecules with antimicrobial properties. Such arsenals with low cytotoxicity are expected to eradicate the ESKAPE pathogens: *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter* spp.

Keywords: conducting polymers; antimicrobial; nanoparticles; ROS; polymer composites

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1. Introduction

Microbial infection or contamination is a serious problem in clinical/hospital settings, medical devices, hygienic products, water purification systems, textile materials, food packaging, and food storage. Antibiotics are designed to interfere with the synthesis of bacterial cell walls, proteins, DNA, and other cellular activities [1]. Other antibiotics act as inhibitors of 30S subunit (aminoglycosides), 50S subunit (chloramphenicol) [2], folic acid metabolism (sulfonamides and trimethoprim) [2], and DNA replication (fluoroquinolones/FQs) [2]. Beta-lactam antibiotics exhibit a wide spectrum against both Gram-negative and Gram-positive bacteria [3]. For instance, bacterial penicillin-binding proteins interact with a beta-lactam ring of antibiotics, therefore they are not available for the synthesis of new peptidoglycan, resulting in disruption of the peptidoglycan layer [4]. Most low molecular weight antibiotics are designed to penetrate all cell membranes and are rapidly excreted from the body [5]. Thus, their high and repeated doses must be given to maintain a therapeutic effect, resulting in serious side effects on the host.

Bacteria have time and find a way to fight back using specific enzymes, e.g., lactamase to open the β-lactam ring to nullify or significantly reduce the efficacy of lactam ring antibiotics [6]. Bacteria can alter their outer membrane permeability or decrease the number of porin channels, resulting in decreased entry of β-lactam antibiotics into the cell. Porins are present in every species of Gram-negative bacteria and even in a group of "Gram-positive" bacteria [7]. A second example is the inactivation of nourseothricin, one of the streptothricin-class aminoglycoside antibiotics that inhibit protein synthesis [8]. N-acetyl

transferase of *Streptomyces noursei* inactivates this antibiotic by acetylating the beta-amino group of the beta-lysine residue [9]. Of importance is vancomycin, a complex antibiotic that binds to the D-Ala-D-Ala terminal of the growing peptide chain during cell wall synthesis [10]. Some bacteria can alter the terminal peptide from D-Ala-D-Ala to D-Ala-D-Lac, or by the development of thickened cell walls, leading to vancomycin resistance [10]. Bacteria are also equipped with efflux pumps [11] in the cytoplasmic membrane, which pump antibiotics out before they reach the target. This is a key mechanism of antibiotic resistance in Gram-negative bacteria. These pumps may be formed by a single component or by multiple components [12]. Bacterial biofilms released by various microbes serve as a protective layer to shield them from the penetration of antibiotics and other harsh conditions [13].

As antibiotic-resistant bacteria emerge, there is an urgent need to develop effective antimicrobial agents to stamp out such bacterial species. Ideally, antimicrobial agents must fulfill several requirements such as a broad antimicrobial spectrum at short contact time; ease of preparation at low cost; high stability at the intended applications and storage; and regeneration after the loss of activity. The use of low molecular weight antimicrobial agents even at suitable amounts in water disinfection, food preservation, and soil sterilization is unfavorable due to their residual toxicity. Synthetic polymers with different molecular weights and biocidal moieties have been considered as a new class of antimicrobial agents to overcome several setbacks associated with antibiotics. At first glance, the adsorption of polycations onto the bacterial cell surface with a negative charge forms an additional barrier to interfere with normal bacterial activities. The polymer molecular weight also plays an important role if the killing effect is significantly dependent on its permeability through the bacterial cell wall. In this context, two well-known conducting polymers, polyaniline (PANI) and polypyrrole (PPY) with various molecular weights have received significant attention due to their easy preparation, low cost, low toxicity, and biocompatibility [14–17]. Antimicrobial polymers or polymeric biocides are also stable and nonvolatile and do not permeate through the skin, i.e., minimal cytotoxicity. However, the utilization of conducting polymers (CPs), e.g., PANI is limited due to its partial solubility and is insoluble in most of the organic solvents [18–20]. There is also infusibility as well as weak processability on different cycle times [21,22]. In general, CPs are also less effective or even ineffective against fungi and their MICs (minimum inhibition concentrations) are considerably higher than those of antibiotics. Enhanced antimicrobial properties can be achieved by functionalized CDs (carbon dots) (f-CDs), copolymers, and polymer nanocomposites with metal oxides or small molecules. Various attempts have been made such as doping with different organic functional groups, copolymerization with other monomers, and forming nanocomposites of metal oxide with conducting polymers to mitigate such disadvantages [23–27]. Silver and copper are extremely detrimental to bacteria at ultralow concentrations, thus, there is a growing trend to fabricate such metal nanoparticles and incorporate them into polymer networks. Conducting polymers form nanocomposites with metal oxide nanoparticles [28–31] exhibiting excellent mechanical, conductive, and antimicrobial properties.

The current review focuses on the antimicrobial properties of two well-known conducting polymers, polypyrrole and polyaniline, and their composites. Antimicrobial polymers have been defined broadly as materials that inhibit or kill microorganisms. These conducting polymers have cationic and amphiphilic structures, two required features for antimicrobial properties. The review highlights their antimicrobial efficacies against different microbial species, followed by some plausible inhibiting/killing mechanisms. Emerging issues regarding the applicability of conducting polymers and their composites in the real world are discussed to guide future studies.

2. Polypyrrole (PPY) Based Composites for Antibacterial Activity

PPY is a conjugated polymer with a positive charge on its backbone chain that can mediate contact with the negatively charged bacterial cell surface through electrostatic

adherence as mentioned earlier. Negative zeta potential is observed for Gram-positive bacteria (prevailing polysaccharides) or Gram-negative bacteria (teichoic acids bonded to the peptidoglycan layer). The average zeta potential of *E. coli* is −44.2 mV, compared to −35.6 mV for Gram-positive *S. aureus* [32]. The additional layer of negatively charged LPS (lipopolysaccharide) in Gram-negative *E. coli* can be attributed to its higher negative potential. However, the zeta potential of Gram-negative *E. coli* is strain-dependent, ranging from −6.76 to −39.87 mV [33]. In contrast, the zeta potential of PPYCl (chloride-doped polypyrrole particles) is zero at pH 14 and ~40 mV at pH 7 [34]. Thus, the polycationic PPY will bind to the negatively charged bacterial wall polymers, leading to the destabilization and disruption of the cell wall equilibrium dynamics. The molecular weight of PPY plays an important role in determining the antimicrobial properties, however, this parameter is still understudied for conducting polymers. For polyacrylates and polymethyl acrylates with side-chain biguanide groups, the optimal molecular weight region ranges from 50 to 120 kDa and the antibacterial activity decreases drastically when the polymers are over 120 kDa. The dependence of antimicrobial properties is partially anticipated based on their permeability through the bacterial membrane. For comparison, high molecular weight soluble PPY has at least 303 pyrrole rings (MW = 67.09) per chain, so its corresponding molecular weight is about 20 kDa [35]. On this basis, PPY could penetrate the bacterial membrane, at least partially, and interact with other intracellular biomolecules.

PPY-based conductive composites have been advocated for anti-biofilm [36,37] and antibacterial applications [15,26,38] against both Gram-positive and Gram-negative pathogens. As an example, a treated fabric with 4 g/m^2 of PPY exhibits log bacterial reductions of 6.0 against *S. aureus* and 7.5 against *E. coli* [39]. The killing effect, however, is not efficient as pathogens often produce negatively charged biofilms, which bind to positively charged antibiotics to prevent the contact between antibiotics and underlying viable pathogens [13]. As discussed later, several conducting polymers including PPY also require contact times of several hours to significantly reduce viable pathogens, which have limited applications. In most "real-world" scenarios, the contact time should be the order of seconds or a few minutes at most. Metal and metal oxide nanoparticles can exert their effect on microbial cells by generating membrane damage, oxidative stress, and denaturation of proteins and DNA. However, nanoparticles tend to aggregate and agglomerate, due to the attraction between nanoparticles such as van der Waals forces and chemical bonds. An ensemble of nanoparticles with high surface-free-energies often reach a stabilized state through agglomerating into micron-scale aggregates with the diminishing total surface area, i.e., reducing antimicrobial activities. Nanoparticles that interacted with long-chain organic molecules will be stabilized in solution through steric interactions, while electrosteric forces arise when an electrostatic charge is present on these molecules. Metal nanoparticles can be associated with conducting polymers with positive charges on the surface, a crucial step for the stabilization of suspensions containing high nanoparticle concentrations.

Considering extreme toxicity of metals to bacteria, PPY has been modified with metal-based nanoparticles (silver [38,40], iron oxide [41,42], zinc oxide [43,44], copper oxide [26,45]), carbon-based material (single-wall carbon nanotube [46], graphene [47]), natural materials (chitosan [48,49], dextrin [50], gelatin [51,52], cellulose [53], and with conjugated polymer matrix [54]). Copper nanoparticles (NPs) decrease the bacterial membrane integrity, resulting in eventually cell death. Similarly, silver NPs damage the structure of the bacterial cell membrane. AgNPs also suppress the activity of some membranous enzymes because of their interaction with sulfur-containing proteins present in the bacterial membrane.

The incorporation of these materials either enhances the density of the electroreactive sides for electrostatic interaction or favors the reactive oxygen species (ROS) formation to enhance the antibacterial activity, as represented in Table 1. Gram-negative *E. coli* and Gram-positive *S. aureus* are often used as two test models. The latter is the second commonest pathogen that causes healthcare-associated infections (HAIs) that occur in one of 25 patients

daily on average in the USA, corresponding to over 2 million patients contracting HAIs per year [55].

Table 1. Reported PPY-based composites for antimicrobial applications.

S. No	Polypyrole Composites	Solvent	Preparation Method	Model Bacteria	MIC	Maximum Inhibition Time (h)	Ref.
1	PPY@CuO	Ethanol, Water (9:1)	sonochemical	*E. coli*, *S. aureus*	1 mg/mL	8	[26]
2	Fe_3O_4@PPY NPs	Water	oxidative polymerization	*S. aureus*, *E. coli*	100 µg/mL	24	[31]
3	PPY@maghemite@ silver	Water	oxidative polymerization	*S. aureus*	2 mg/mL	18–24	[42]
4	B-PPY/ZnO	Ethanol	Photo-polymerization	*E. coli*	0.03 mg/mL	24	[43]
5	PPY@Ag/RGO	Polyvinyl pyrrolidone & ethylene glycol	sonication	*E. coli*	0.2 mg/mL	24	[47]
6	Cellulose nanopaper/Chitosan/PPY	Water	polymerization	*S. aureus*, *E. coli*	-	48	[48]
7	Chitosan-gelatin/ tannic acid/PPY	Water	polymerization	*S. aureus*, *E. coli*	-	18	[51]
8	PPY-gelatin cryogel	Gelatin	polymerization	*S. aureus*, *E. coli*	-	24	[52]
9	Macroporous Melamine Sponges with PPY	Poly(N-vinylpyrrolidone) and nanosilica	precipitation polymerization	*S. aureus*, *E. coli*	-	24	[56]
10	Ag/PPY	Water	polymerization	*E. coli*	-	30	[57]
11	ZFCN@PPY	Water	oxidative polymerization	*E. coli*	0.5 mg/mL	24	[58]
12	Nanocellulose-PPY	Water	chemical polymerization	*B. subtilis*, *E. coli*	-	24	[59]
13	Polystyrene@ (silver–PPY	Water	oxidative polymerization	*E. coli*, *S. aureus*	50 µg/mL	24	[60]

RGO: reduce graphene oxide, NPS: nanoparticles, ZFCN: zinc ferrite/graphitic carbon nitride, B-PPY: bentonite intercalated with PPY.

Over the past few years, metal-based PPY composites have gained high attention toward antimicrobial applications. The antimicrobial mechanism of polymer-metal nanoparticle composites consists of the following steps [61]: (i) The adsorption of bacteria on the polymer surface by charge interaction; (ii) diffusion of water-surrounded bacteria with O_2 to the surface of embedded nanoparticles; (iii) metal ions are released due to dissolution or corrosion processes; (iv) and metal ions can damage the bacterial membrane allowing their subsequent further intake into the intracellular region [62]. The killing effect is also related to the formation of two reduced forms of molecular oxygen (O_2), known as hydrogen peroxide (H_2O_2) and superoxide ($O_2^{\bullet -}$) as metals can easily acquire electrons from a donor. Such ROS can induce oxidative stress to damage bacterial proteins, lipids, and DNA if they exceed the bacterial antioxidant capacity [63]. Additionally, some metals if present in the medium will react with H_2O_2 to produce hydroxide (OH^-) and the highly reactive hydroxyl radical ($OH^{\bullet}$), known as the Fenton equation

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH^{\bullet} \quad (1)$$

For Cu-induced cellular toxicity, Cu^{2+} is first reduced to Cu^+ by superoxide or reducing agents, e.g., ascorbic acid, if provided in the medium, followed by the formation of hydroxyl radicals from hydrogen peroxide via the Haber–Weiss reactions [64]:

$$O_2^{\bullet -} + Cu^{2+} \rightarrow O_2 + Cu^+ \quad (2)$$

$$Cu^+ + H_2O_2 \rightarrow Cu^{2+} + OH^- + OH^{\bullet} \quad (3)$$

As the most powerful oxidizing radical, $OH^{\bullet}$ can react with almost any biological molecule [65]. It causes oxidative damage by abstracting the hydrogen from a carbon-centered protein or an unsaturated fatty acid to form a protein or lipid radicals, resulting in total degradation of the protein backbone and loss of essential protein function. Albeit the antimicrobial activity of metals is mainly attributed to the presence of ROS, other plausible biocidal activities of metals are summarized below:

- Form covalent bonds with S (e.g., thiol of glutathione) to deplete this antioxidant reserve [66].
- Metal ions or their complexes can replace original metals present in biomolecules leading to cellular dysfunction [67], known as ionic mimicry or molecular mimicry. A known target is the Fe–S clusters of bacterial dehydratases that are particularly vulnerable to site-specific inactivation by toxic metals [68].
- Cupric ions (Cu^{2+}) can form organic complexes with bacterial S, N, or O-containing functional groups to affect the conformational structure of nucleic acids and proteins by oxidative phosphorylation and osmotic balance.
- Upregulate genes involved in the elimination of ROS-generating oxidative stress [66].

From an application viewpoint, silver is widely used because of its well-known biocidal activity. A cylindrical PPY/silver chloride polymer composite obtained by one-pot synthesis shows significant antimicrobial activity against *E. coli* [69]. Self-aggregated methyl orange is used to create a cylindrical shape to serve as a template for polymer growth. Silver nanoparticle embedded PPY composites can be prepared by an in situ polymerization method [70] and comparing the activity by varying the concentration of Ag^{+} ion. Increasing Ag^{+} content in the composite bacterial provokes an increase in the inhibition of cell growth. The bacterial eradication mechanism indicates that the electrostatic interaction between the positively charged composite and negatively charged bacteria is responsible for cell death. In another study, mesoporous silica incorporated PPY/silver nanocomposite is explored for bacterial eradication [71]. Silver nanoparticles/single-walled carbon nanotubes/Polypyrrole (AgNPs/SWCNT/PPY) core, shelled cost-effective ternary nanocomposite is prepared using a one-pot synthesis method [46]. The prepared ternary composite unravels the following order of performance: *B. cereus* > *E. coli* > *P. aeruginosa* > *Methicillin-resistant S. aureus* at 0.048 mg/mL within 24 h. The synergistic behavior between AgNPs, SWCNTs, and PPY, increases the inhibition efficiency of the composite. An iron oxide-containing PPY@ polyxanthone triple-layer core-shell-shell composite has been developed [54]. Iron oxide nanoparticles are incorporated into a thin coating of polyxanthone triazole before the deposition of the PPY layer. Pyrrolonium, xanthone, triazole ring, and Fe_3O_4 collectively damage the cell wall, causing the leakage of essential intracellular components. A CuO@PPY nanocomposite prepared by sonochemical synthesis shows complete eradication of *E. coli* and *S. aureus* in 8 h [26]. Of particular value is the synthesis of Zn decorated copper oxide PPY and PANI composites with inhibition activities against *E. coli*, and *S. aureus* [45]. The addition of ZnO into the composite enhances the zeta potential (Figure 1a,b) from negative to closer to zero, and the release of ROS (Figure 1c) plays the main role in increased antibacterial activity. A rosemary extracted palladium nanoparticle combined PPY nanotube-shaped composite has been evaluated for its antimicrobial activity against *E. coli*, *K. pneumoniae*, *B. subtilis*, and *S. aureus* eradication [72]. The prepared composite shows enhanced antimicrobial activity compared to pristine PPY.

The PPY/natural material-based composite exhibits remarkable properties against Gram-positive and Gram-negative pathogens. A PPY/chitosan (CTN) nanocomposite prepared by dispersion polymerization exhibits the following order of activity [49]: PPY/CTN nanocomposite > PPY > CTN against *E. coli*. To improve the antibacterial performance and applications, zinc oxide (ZnO) can be incorporated into the PPY/chitosan-based composite [44]. The ternary composite (PPY/chitosan/ZnO) at 150 µg/mL exhibits excellent antimicrobial performance compared to PPY/chitosan (Figure 2). ZnO triggers the enhanced ROS generation, which is attributed to the bacterial inhibition mechanism.

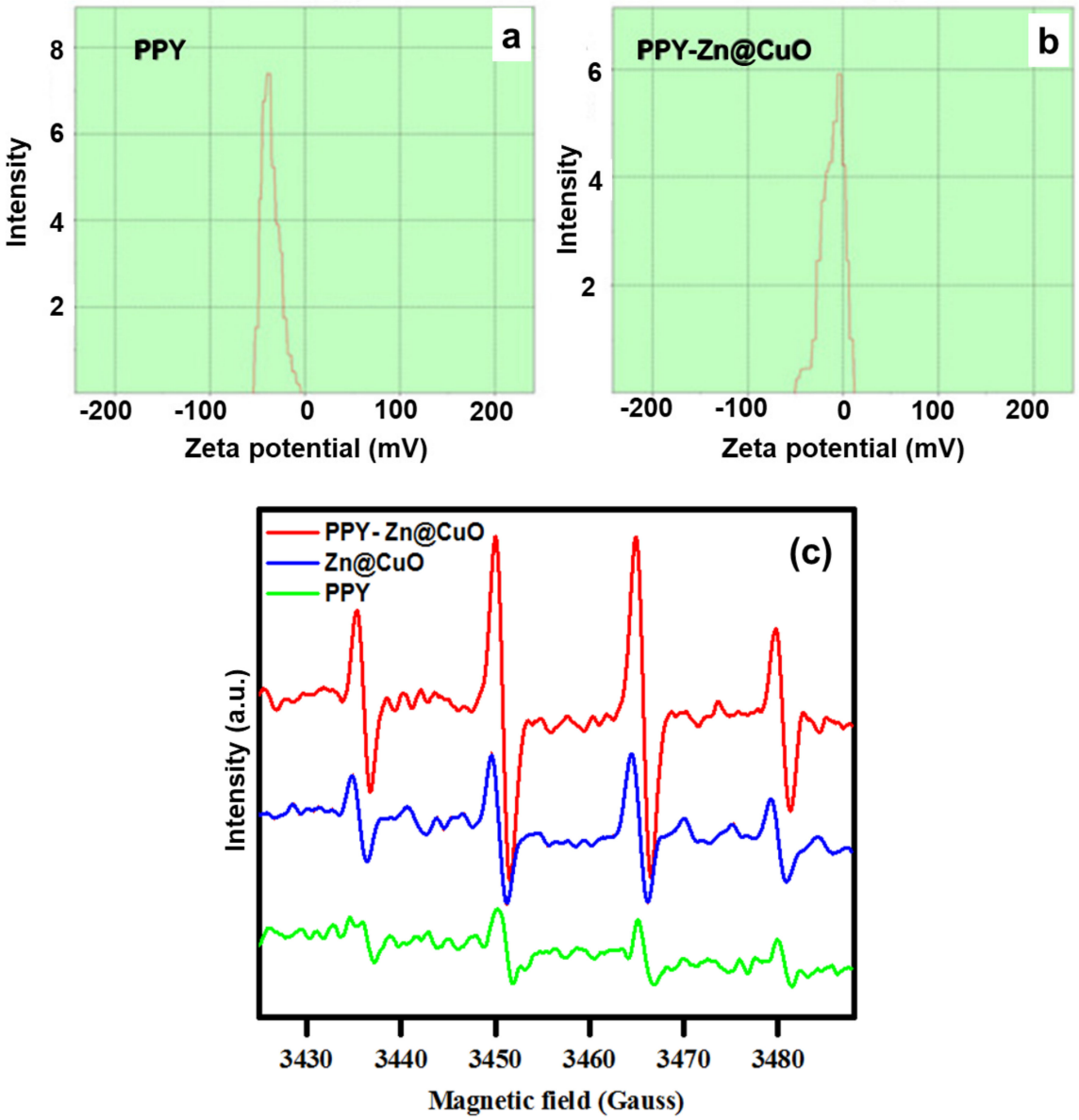

Figure 1. Zeta potentials of (**a**) PPY, and (**b**)PPY−Zn@CuO (**c**) Electron paramagnetic resonance (EPR) measurement for PPY, Zn@CuO, and PPY−Zn@CuO (Reprinted from Ref. [45]).

Polymer composites comprising dextrin and PPY can be prepared by in situ polymerization by varying the composition of PPY and tested against Gram-negative (*P. aeruginosa* and *E. coli*) and Gram-positive (*B. subtilis* and *S. aureus*). The polymer composites exhibit the highest microbial inhibition activity against *P. aeruginosa*, followed by *S. aureus* [50]. However, the composite only shows moderate to weak activity against *B. subtilis* and *E. coli*. A nanocellulose functionalized multilayer PPY composite has been synthesized [53] and evaluated for its antimicrobial activity against *B. subtilis* and *E. coli*. PPY is effective in destroying germs that came into contact with the coated surface. A multifunctional composite of chitosan-gelatin/tannic acid/PPY has been attempted for *E. coli* and *S. aureus* eradication [51].

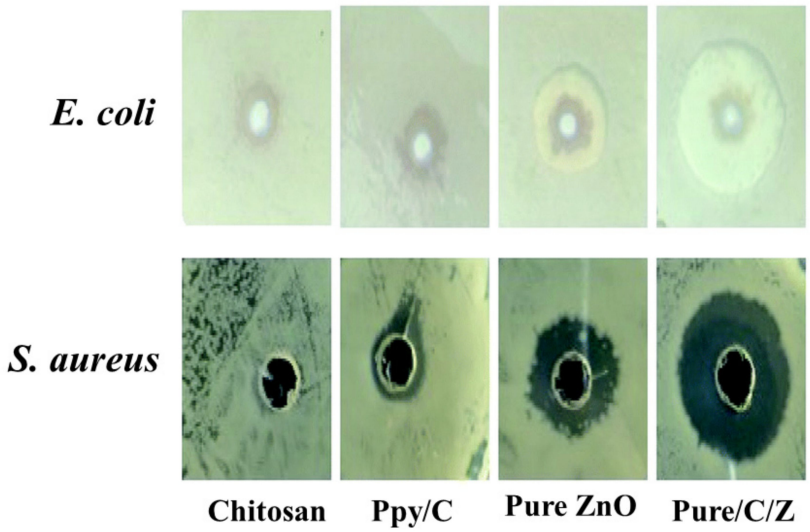

Figure 2. Zone of inhibition of chitosan, PPy/C, Pure ZnO (Z), and PPy/C/Z against *E. coli* and *S. aureus*. (Reprinted from Ref. [44]).

3. Polyaniline (PANI) for Metal/Metal Oxides-Based Composites

Polyaniline (PANI) contains antibacterial activity against selected pathogens for various reasons, such as the reduced concentration of residual low molecular weight byproducts, the length of the polymer chain, electrostatic interaction, and the amino groups of PANI. PANI with antimicrobial properties is somewhat anticipated as phenol is a strong antimicrobial agent, which can disrupt bacterial membranes. PANI shows unique proton dopability, excellent redox recyclability, variable electrical conductivity, superior thermal, and chemical stability. Like PPY, positively charged PANI binds to the bacterial membrane with a negative charge, as the first step to interfere with bacterial activities to support survival, growth, and proliferation. PANI synthesized by chemical oxidative polymerization of aniline using ammonium persulfate has a measured molecular weight below 100 kDa [73]. Thus, it is likely able to penetrate bacterial cells to interact with different intracellular biomolecules. The antimicrobial mechanism of PANI also involves ROS production to damage proteins and/or the cell membrane, resulting in cell lysis. PANI is more active against *E. coli* in aerobic, compared to anaerobic conditions and such results imply that PANI likely involves the production of H_2O_2. The supersensitivity of *E. coli* ΔkatG mutant to PANI confirms that the mutant without Δ*kat*G is unable to scavenge endogenous H_2O_2 and responds to oxidative stress [74]. Similarly, *E. coli* Δ*isc*S mutant is sensitive to H_2O_2 as this mutant is unable to modify DNA for protection against oxidative stress [75].

Like PPY, PANI has been used to form several composites with metals and metal oxides to improve the antibacterial activities of composites. An example is the synthesis of an Ag-doped ZnO/PANI composite with antibacterial activity [76]. The photocatalytic activity of ZnO improves with the dopant of Ag to form AZO ($Ag_{0.02}Zn_{0.98}O_{0.99}$). Combined sonication and stirring are applied for the synthesis of AZO/PANI composite preparation. The antibacterial effect of AZO/PANI is more pronounced in a composite PANI with AZO (60%), compared to PANI. The mechanism reveals that PANI coating with AZO could stabilize the e^- and h^+ generated from AZO. The stabilized e^- and h^+ then react with adsorbed O_2 and H_2O to form ROS, which damage the cell membrane and other intramolecular components. HCl-doped PANI is synthesized via oxidative polymerization of aniline using HCl and potassium persulfate as a dopant and oxidizing agent, respectively [77]. For comparison, a composite of PANI/ZnO is prepared by oxidative polymerization of aniline in ZnO dispersion. PANI shows less antibacterial activity for *E. coli* with a 9 mm inhibition zone and inefficient activity for *S. aureus*. The antibacterial efficiency of ZnO nanoparticles and PANI/ZnO nanocomposite (NC) was higher for *S. aureus*, compared to *E. coli*. The antibacterial activity of PANI/ZnO NCs increases with increasing ZnO content in the com-

posite. A sonochemical approach has also been conducted for preparing PANI-CuO, SiO_2, and TiO_2 [78]. The PANI is prepared by dissolving aniline in acidic conditions (HNO_3) with carbon dots (CDs). The CDs serve as an initiator to polymerization of aniline under UV light for 48 h. The synthesized PANI is further processed to make composites with different metal oxides. The prepared PANI-metal oxide composites (CuO, SiO_2, and TiO_2) are evaluated for the eradication of *P. aeruginosa* and *K. pneumoniae*. An individual PANI, CuO, SiO_2, or TiO_2 has no lethal effect, whereas the composites of PANI-CuO and PANI-TiO_2 completely suppress the growth of *P. aeruginosa* after 6 h of incubation, compared with 12 h for the PANI-SiO_2 composite (Figure 3). PANI stimulates the release of H_2O_2, promoting the liberation of $OH^{\bullet}$ radicals to oxidize bacterial biomolecules, leading to cell lysis. PANI is polymerized from aniline in acidic conditions with $(NH_4)_2S_2O_8$ under ultrasonication. Alone PANI has no antibacterial effect, whereas PANI with Ag exhibits a pronounced antibacterial effect against *Salmonella species*, *B. subtilis*, *E. coli*, and *S. aureus* [79]. Among them, the PANI/Ag nanoporous composite presented better eradication against *Salmonella* species with an inhibition zone of 22.5 mm at a concentration of 400 ppm (PANI). A ternary Ag–Cu_2O/PANI composite is highly effective for *S. aureus* and *P. aeruginosa*, compared to PANI, Ag, Cu_2O, and Cu_2O/PANI [80]. Overall, the bacteriostatic percentage of Ag–Cu_2O/PANI on *P. aeruginosa* and *S. aureus* is 98.94% and 97.2%, indicating the best antibacterial effect on *P. aeruginosa* and *S. aureus.* ROS play a crucial role in bacterial eradication under illumination. The Ag–Cu_2O/PANI composite produces the highest ROS, followed by Cu_2O/PANI, which far exceeds the amount of ROS produced by Cu_2O. The combination of Cu_2O and AgNPs results in the Schottky barrier at the metal-semiconductor interface. Thus, the photoexcited charge separation efficiency of Cu_2O is significantly improved, and the addition of PANI further augments the charge separation efficiency of Cu_2O. The Cu_2O and PANI can be excited to generate e^- and h^+ under UV-visible illumination. The intensity of the PL spectra (excited at 325 nm) of Cu_2O/PANI and Ag–Cu_2O/PANI composites is significantly lower than that of Cu_2O. Combining Cu_2O with Ag and PANI can effectively prevent the recombination of Cu_2O electron-hole pairs, thus maintaining its high photocatalytic effect. Simultaneously, the Ag-Cu_2O/PANI composite exhibits better antibacterial effects over the other three samples throughout the period (30 days) due to the synergistic bactericidal action of Ag, PANI, and Cu_2O. The antibacterial effect of PANI-bimetal composites has been evaluated [81]. Au-Pt colloidal solutions are initially mixed with pristine PANI, synthesized from aniline in the presence of sulfuric acid and ammonium persulfate. The antibacterial activity of Au colloidal, Au–Pt colloidal, pristine PANI, PANI-Au nanocomposite, and PANI-Au–Pt nanocomposite against *B. subtilis*, *S. aureus*, *E. coli*, and *V. cholerae*, was studied. Negligible antibacterial activity is noted for Au and Au-Pt colloidal solutions, whereas the PANI-Au–Pt nanocomposite displays an inhibition zone of 33 mm against *B.subtilis*, 30 mm for *Staphylococcus* sp., 26 mm for *E. coli*, and 23 mm for *V. cholera*. The PANI-Au nanocomposite also inhibits *B. subtilis* (31 mm) and *Staphylococcus* sp. (28 mm), followed by *E. coli* (23 mm) and *V. cholerae* (18 mm). As shown in Figure 4a,b, pristine PANI only inhibits *B. subtilis* (19 mm), *Staphylococcus* sp. (17 mm), *E. coli* (15 mm), and *V. cholerae* (12 mm). Of value is the efficacy of multifunctional polyaniline/copper/TiO_2 (PANI/Cu/TiO_2) ternary nanocomposites [82]. The PANI reacts with copper (II) chloride dihydrate in methanol at pH 3 under stirring. For the preparation of PANI/Cu/TiO_2, TiO_2 is added to the Cu solution before adding aniline. TiO_2 nanoparticles have negligible antibacterial effects, whereas polyurethane coated with a 5% PANI/Cu/TiO_2 nanocomposite possesses a strong antibacterial effect on *S. aureus* and *B. cereus* after 60 min of exposure, whereas PANI has a negligible effect. The type of metal dopants also plays an important role in antimicrobial properties. PANI, PANI/ZrO_2, or ZrO_2 at 2 mg/mL exhibits 99.9% bactericidal efficiency against *E. coli* after 0, 2, and 12 h of incubation [83]. However, PANI and PANI/ZrO_2 at 1 mg/mL have no antibacterial activity, compared to 99.9% for ZrO_2 at this concentration. The minimum inhibition concentration (MIC) of PANI and PANI/ZrO_2 is 1 mg/mL for *S. aureus* and 2 mg/mL for *E. coli*. In the case of *S. aureus*, 2 mg/mL of PANI, ZrO_2, and PANI/ZrO_2 is required to reach 99.9% eradication after 6 h of incubation. Thus, the antibac-

terial efficiency of PANI and its composites depend on doping metals and their levels in such composites. The antibacterial properties of PANI-based composites are summarized in Table 2.

Table 2. Summary of PANI based composites and their antibacterial properties.

Composites Name	Metal/Metal Oxides	Method	Model Bacteria	Concentration MIC	Concentration MBC	ZOI (mm)	Max. Inhibition Time	Ref.
Ag-doped ZnO/PANI	Ag/ZnO	sonication and stirring	*E. coli* *S. aureus,* *C. albicans*	10 mg/L 10 mg/L 5 mg/L	25 mg/L 25 mg/L 10 mg/L	35.4 37.4 39.8	24 h	[76]
PANI/ZnO NCs	ZnO	Stirring	*E. coli* *S. aureus*	-	-	13.0 16.0	-	[77]
PANI-CuO PANI-SiO_2 PANI-TiO_2	CuO SiO_2 TiO_2	Stirring and Sonication	*P. aeruginosa*	220 µg/mL	-	-	6 h 12 h 6 h No effect	[78]
			K. pneumoniae	220 µg/mL	-	-	12 h 6 h	
Ag/PANI Nanoporous Composite	Ag	Oxidative polymerization under visible light irradiations lamp	*E. coli* *S. aureus* *B. subtilis* *Salmonella*	- - - -	- - - -	18.0 22.5 19.0 20.0	24 h	[79]
Ag-Cu_2O/PANI	Ag/Cu_2O	Stirring	*S. aureus* *P. aeruginosa* *B. subtilis*	75 µg/mL 50 µg/mL	- -	- - 33.0	30 days (High long-term ABA)	[80]
PANI-Au–Pt Nanocomposites	Au-Pt	Stirring	*S. aureus* *E. coli* *V. cholerae*	25 µg/mL	25 µg/mL	30.0 26.0 23.0	24 h	[81]
PANI/Cu/TiO_2	Cu/TiO_2	Stirring	*E. coli* *Salmonella* *B. cereus* *S. aureus*	- - - -	- - - -	- - - -	24 h	[82]
PANI-ZrO_2 composite	ZrO_2	Stirring	*E. coli* *S. aureus*	- -	0.002g/mL 0.001g/mL	14.0 18.0	24 h	[83]
PANI@g-C_3N_4	g-C_3N_4	-	*E. coli* *S. pneumoniae*	60 µg/mL 60 µg/mL	- -	16.0 18.0	24 h	[84]
PANI/MWCNT	MWCNT	Stirring	*E. coli* *S. aureus*	- -	- -	20.0 19.0		[85]

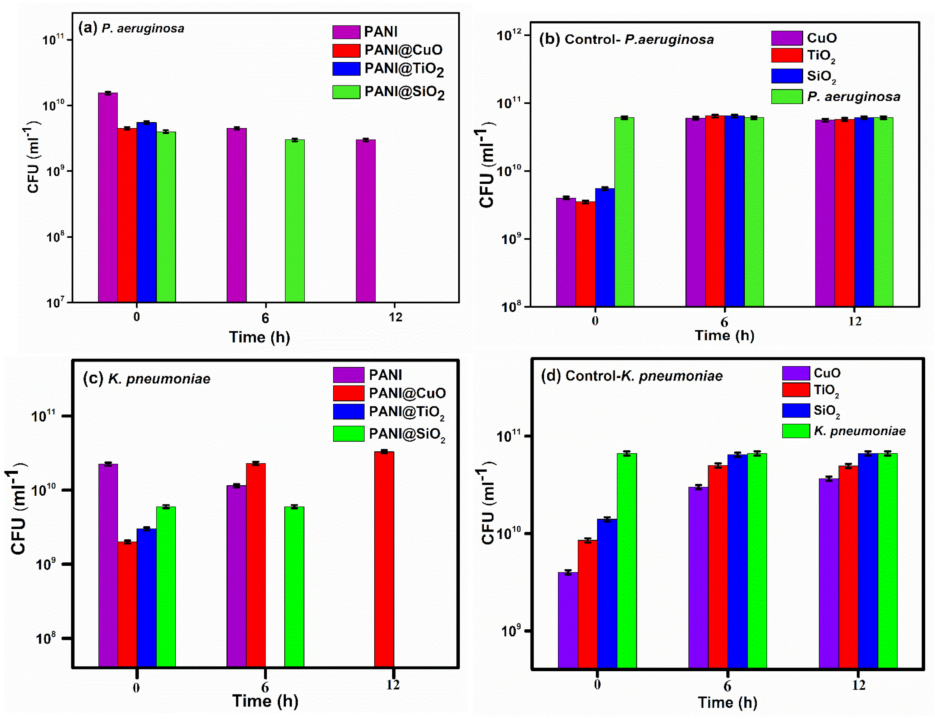

Figure 3. The bactericidal effect of PANI-CuO, PANI-TiO_2, PANI-SiO_2 on the growth of *P. aeruginosa* (**a**) and *K. pneumoniae* (**c**) and the effects of CuO, TiO_2, and SiO_2 on *P. aeruginosa* (**b**) and *K. pneumoniae* (**d**) (Reprinted from Ref. [78].

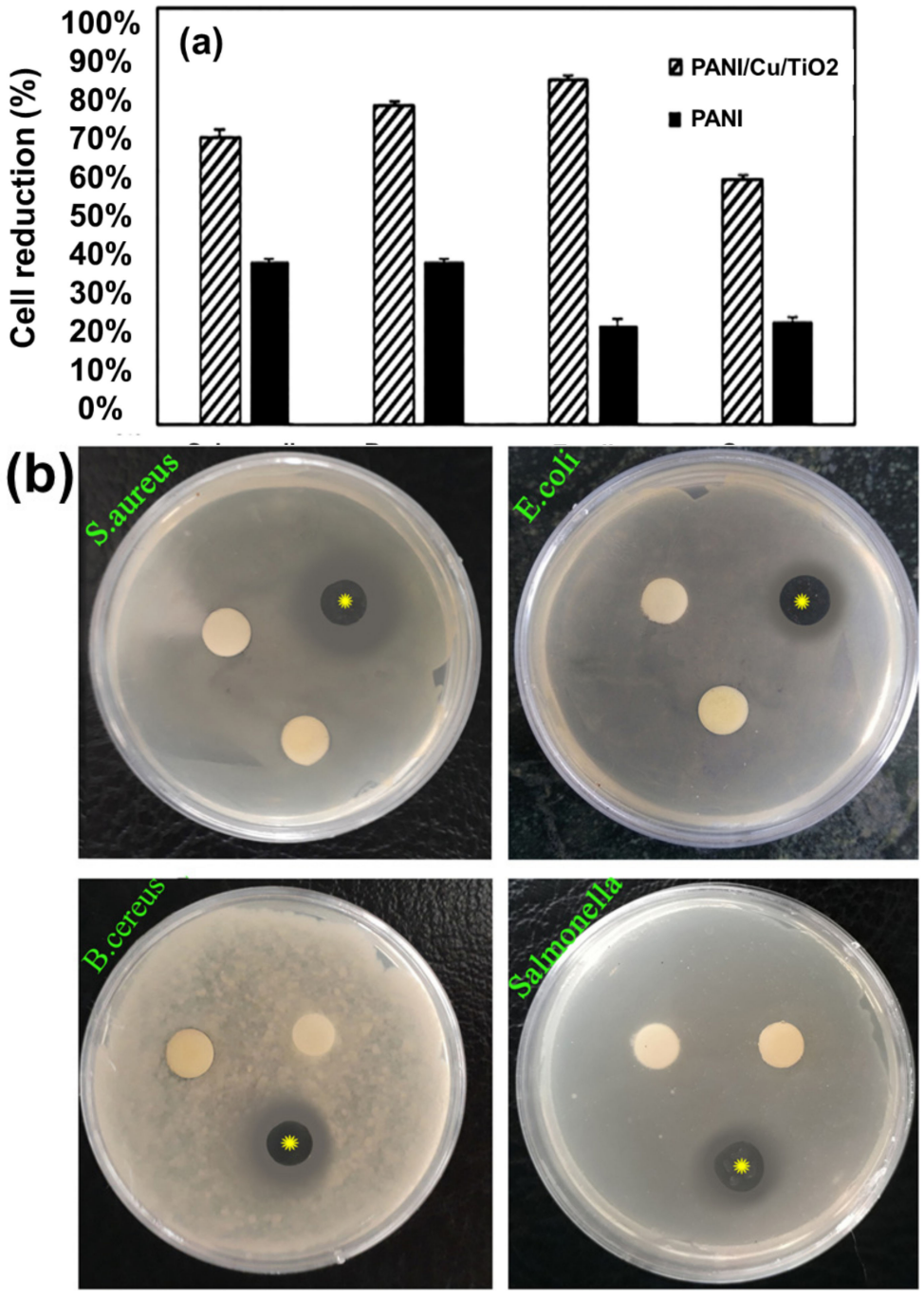

Figure 4. *Cont.*

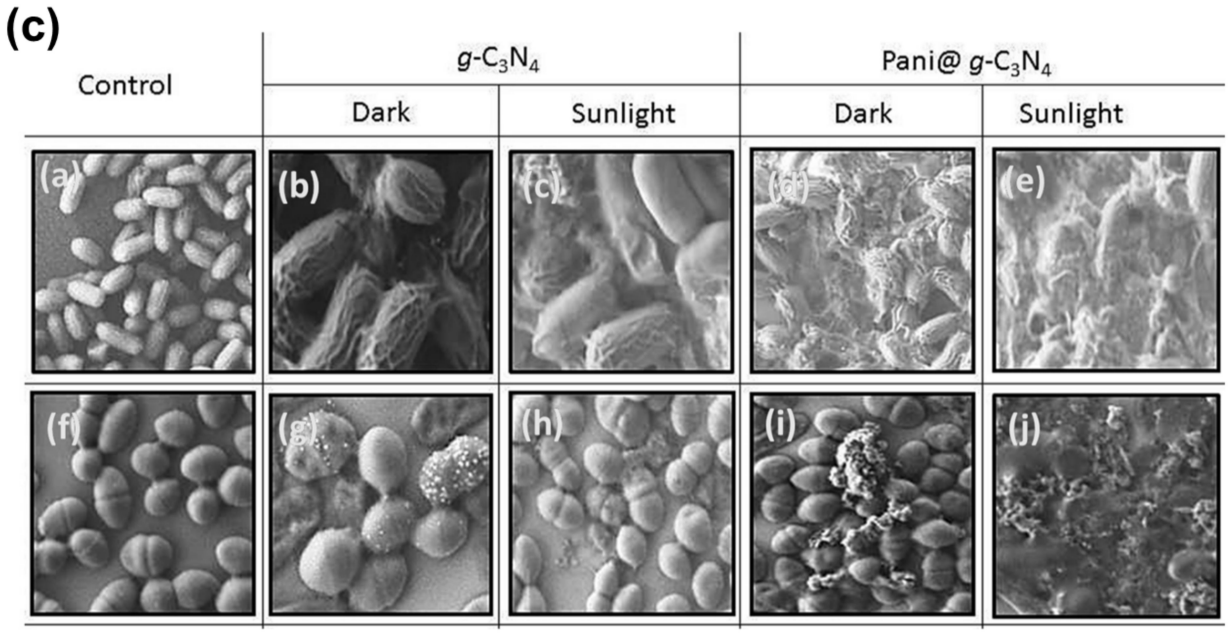

Figure 4. (**a**) 5 wt % content of PANI/Cu/TiO_2 nanocomposite and pristine PANI. (**b**) Antibacterial effect of a blank specimen, blank polyurethane coating (non-starred), and polyurethane coated with 5 wt%-PANI/Cu/TiO_2 content. (Reprinted from Ref. [82]). (**c**) The micrographs labeled (a) and (f) control *E. coli* and *S. pneumonia*, (b) and (g) are g-C_3N_4 treated *E. coli* and *S. pneumoniae* in the dark, (c) and (h) are g-C_3N_4-treated *E. coli* and *S. pneumoniae* under sunlight (d) and (i) are PANI@g-C_3N_4-treated *E. coli* and *S. pneumoniae* in the dark while (e) and (j) are PANI@g-C_3N_4-treated *E. coli* and *S. pneumoniae* under sunlight, respectively. (Reprinted from Ref. [84]).

4. Polyaniline (PANI) for Carbon Material-Based Composites

Polymeric composites containing carbon-based nanomaterials offer a wide range of antibacterial properties. Due to their superior antimicrobial activities, they have been investigated for food packaging. PANI also forms composites with larger carbon materials such as graphitic carbon nitride (g-C_3N_4) and multiwalled carbon nanotubes (MWCNT) with good bactericidal properties. Both g-C_3N_4 (75 μg/mL) and PANI@g-C_3N_4 (60 μg/mL) exhibit elevated growth inhibition against *E. coli*, compared to 100μg/mL and 60 μg/mL, respectively, against *S. pneumoniae* [84]. The zone inhibition is 14 and 16 mm for *E. coli* and 15 and 18 mm for *S. pneumoniae* with 100 μg dose/disks of g-C_3N_4 and PANI@g-C_3N_4 (Figure 4c). The bacterial killing activity of g-C_3N_4 under sunlight increases 33% for *E. coli* and 25% for *S. pneumoniae*. However, PANI@g-C_3N_4 in the daylight, the antibacterial activity was 50 and 58% against *E. coli* and *S. pneumoniae.* The photoinactivation of *E. coli* and *S. pneumoniae* by g-C_3N_4 and PANI@g-C_3N_4 revealed the adsorption of g-C_3N_4 and PANI@g-C_3N_4 to negatively charged bacterial cell surface via electrostatic adherence. The adsorbed visible light by g-C_3N_4 and PANI@g-C_3N_4 produces e^-/h^+ pairs and generates $OH^\bullet$ radicals by a series of reactions to induce the photoinduced bacterial death. A ternary composite based on silver-supported PANI/MWCNT composite exhibits antimicrobial properties [85]. Ag NPs-PANI is prepared by in situ polymerizations from silver nitrate, dextrose, aniline, sodium dodecyl sulfate, and ammonium persulfate. Ag-NPs−PANI/MWCNT nanocomposites are then prepared by stirring for 12 h with MWCNTs. The AgNPs−PANI/MWCNT nanocomposites presenting 20- and 19-mm zones of inhibition at 20 μL/mL are higher than Ag NP and AgNPs−PANI for *E. coli* and *S. aureus* (Figure 5). This bactericidal activity is comparable with two reference antibiotics at 10 μg/mL; streptomycin and penicillin with an inhibition zone of 20 and 22 mm, respectively for *E. coli*. The good dispersion of NCs results in a higher surface area of AgNPs and the acidic functional group of PANI leads to bacterial inactivation. The several chemical factors of PANI, such as surface hydrophilicity,

polymer chain length, and molecular weight, are attributed to the enhanced permeability of the bacterial membrane. Overall, incorporating CNMs (carbon nanomaterials) with PANI composite makes superior eradication against both Gram-positive and Gram-negative bacteria. The mechanisms of antibacterial and advantages of PANI with and without CNMs are described in the modeling diagram (Figure 6).

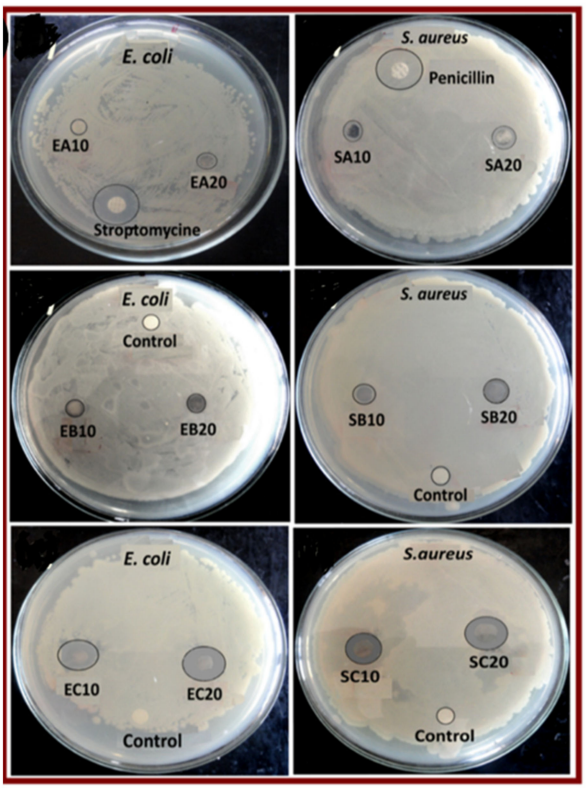

Figure 5. Zone of inhibition observed of AgNPs−PANI, Ag NPs−PANI/MWCNTs *on E. coli* and *S. aureus.* (Reprinted from Ref. [85]).

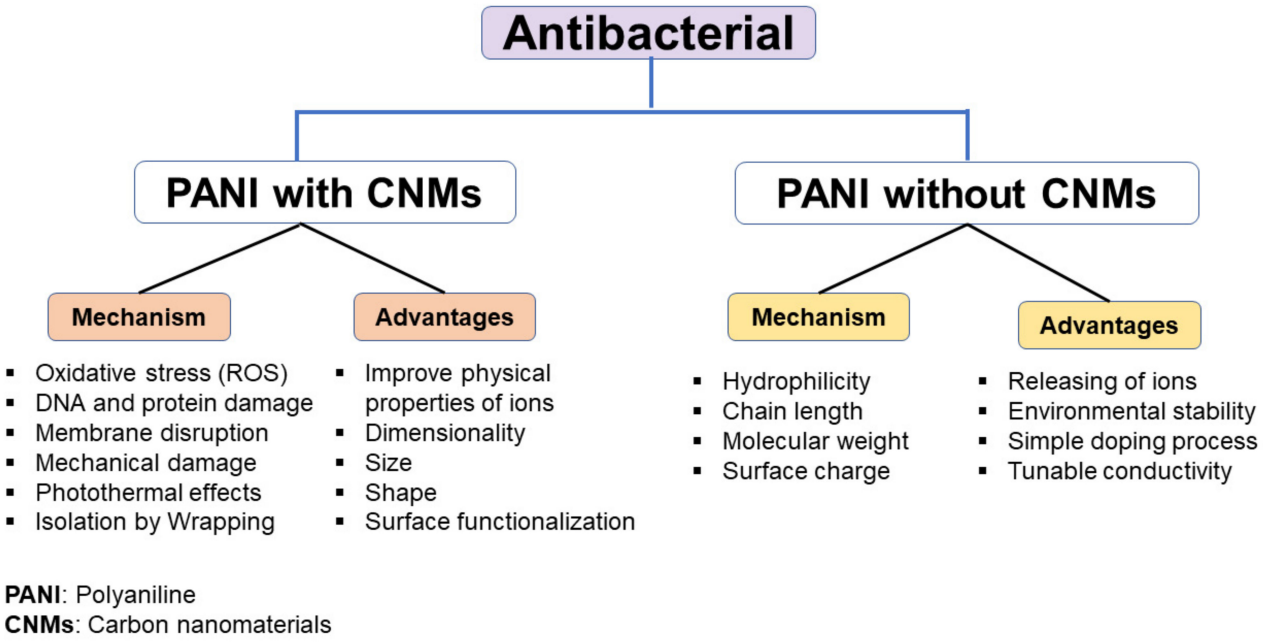

Figure 6. The advantages and mechanisms of the PANI composites with and without CNMs.

5. Antimicrobial Mechanisms

Conducting polymers can form polymer composites with metal/metal oxide nanoparticles with enhanced antimicrobial properties. Metal and metal oxide nanoparticles with different shapes, roughness, and positive zeta potentials are ideal antimicrobial agents against bacteria with negatively charged membranes [86]. Silver, copper oxide, and titanium oxide exhibit antimicrobial properties against several bacteria [87]. Such metal oxide nanoparticles could be developed for therapeutic applications and coatings of medical devices, provided their cytotoxicity, i.e., effect on humans, is below the maximum allowable levels. However, they can also be extended to food packaging, fabrication of textiles, and decontamination of water. Ti, Cu, and Ag nanoparticles are known to be cytotoxic to various human cell lines [88,89] therefore, other metal oxides are more applicable to medical applications as exemplified by ZnO, MgO, Mn_3O_4 (trimanganese tetroxide), and Fe_3O_4 (magnetite). PANI@CuO, PANI@TiO_2, and PANI@SiO_2 show different antimicrobial activities against *P. aeruginosa* and *K. pneumoniae*, two common Gram-negative pathogens.

Positively charged metal oxide nanoparticles exhibit electrostatic interaction with the electronegative groups of the polysaccharides in the membrane. The accumulation of such oxide nanoparticles creates pits in the membrane, leading to a drastic change in membrane permeability. Small nanoparticles with high surface areas are most effective because the membrane pores are in the order of nanometers. Nanoparticles then penetrate inside bacteria and trigger other effects. Unlike the use of antibiotics, the antimicrobial mechanisms of metal oxide nanoparticles are non-specific and not well-established. One possibility is the effect on the microbial respiration system by the generation of ROS from metal oxide particles. ROS has been known to inhibit microbial enzyme activity and DNA synthesis and interrupt the energy transduction (replication of ATP) due to the oxidation of microbial polyunsaturated fatty acids and amino acids [90]. Metal oxide nanoparticles also target microbial cell walls, compromising their normal cell wall-membrane synthesis, leading to eventual cell death (Figure 7). Hydrogen peroxide and O_2^- invoke less acute stress reactions and can be neutralized by microbial catalase and superoxide dismutase. Superoxide and hydrogen peroxide also damage iron-sulfur clusters to release ferrous iron. This iron then reacts with hydrogen peroxide (the Fenton reaction) to liberate hydroxyl radicals, which damage DNA, lipids, and proteins or oxidize the deoxynucleotide pool. To date, there is no microbial pathway against the OH radical attack.

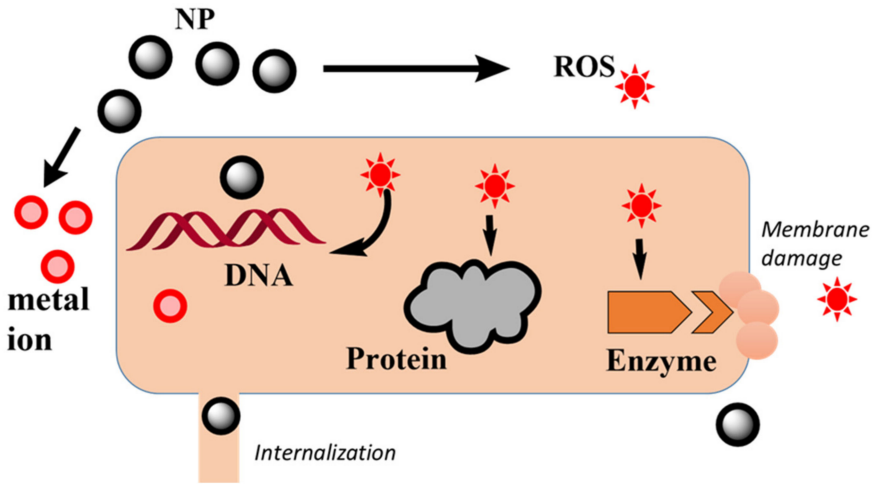

Figure 7. Metal oxide nanoparticles can release metal ions and reactive oxygen species (ROS), two important components that interact strongly with microbial protein, DNA, biomolecules, and enzyme activity that support cell growth and proliferation. ROS encompassing $^{\cdot}OH^{\bullet}$, $^1O_2$, H_2O_2, and superoxides (O_2^-) invoke oxidative lesions, oxidative stress, and membrane lipid peroxidation to damage proteins and nucleic acids.

Metal ions released by nanoparticles compete with metal elements that are essential for the activities of microbial enzymes, catalysts, and other co-factors. The DNA helical structure by inter-and intra-DNA crosslinking is altered upon its binding to metal ions. Like the OH radical, metal ions oxidize the amino acids of enzymatic side chains, resulting in carboxylated enzymes with lost catalytic activities or protein degradation. Metal ions also decrease ATPase activity, an essential enzyme that modulates the membrane potential, an important parameter for preserving membrane integrity. In this context, it is logical to combine conducting polymers and metal oxide nanoparticles to form a new class of antimicrobial agents. Another conducting polymer is polythiophene, which can be combined with helical tri(ethyleneglycol)-functionalized poly-isocyanides (PICs) hydrogel to form a composite with excellent antimicrobial effects against *E. coli*, *B. subtilis*, and *C. albicans* [91]. The composite shows higher ROS production efficiency under red light (below 600 nm).

Iron oxide-based magnetic nanoparticles (MNPs) have extensively been advocated for bacteria sensing due to their magnetic property and high specific surface area [92]. For bacterial separation (from different species) or sensing, various antibodies, antibiotics, antimicrobial peptides, bacteriophages, as well as aptamers have been modified on the surface of MNPs for bacteria labeling and separation under a magnetic field. Other biomedical applications of MNPs encompass magnetic hyperthermia, enhancing magnetic resonance imaging (MRI) data, supplementing tissue engineering efforts, and improving the delivery of drugs toward the treatment and monitoring of cancer and infectious diseases [93]. Iron oxide nanoparticles (IONP) with negative surface charges have insignificant antimicrobial activity against *Bacillus subtilis* and *Escherichia coli*. However, chelating with chitosan results in a significant increase in the antimicrobial propensity of IONP, which could be attributed to higher ROS production [94]. The cytotoxic aspect of maghemite (Fe_2O_3) nanoparticles internalized into cells has been investigated by Blanc-Béguin et al. [95]. There is a change in the morphology of *E. coli*, exposed to a high concentration of γ-Fe_2O_3, leading to abnormal growth and disruption of the division process [96].

The poor control of nanoparticle agglomeration is a major drawback of the use of metal nanoparticles in suspended solutions. Nanoparticles are stable in the suspension if they have a sufficiently strong barrier that prevents aggregation. Metal nanoparticles including magnetic nanoparticles can also be associated with other nanostructures including biopolymers, e.g., chitosan [97–99], and conducting polymers for improving their stability, leading to an array of potential applications. Nanoparticles are commonly stabilized through the adsorption of a dispersant layer or adlayer around the particle surface. Like chitosan, conducting polymers are protonated and carry positive charges. Thus, they interact with negatively charged nanoparticles electrostatically. The formation of a conducting polymer layer of an appropriate thickness is crucial for the stabilization of suspensions containing high nanoparticle concentrations.

6. Cytotoxicity Aspects and Antimicrobial Mechanisms

As fast-developing materials for antimicrobial applications, the cytotoxicity related to the conducting polymers and their nanocomposites is of great importance [100,101]. Biocompatibility is the capability of the polymer nanocomposites to coexist with cells and tissue without damage. However, the toxicity of the materials is depending on the size, chemical composition, and shape. The cytotoxicity of conducting polymers is different from the globular polymers [102]. Hence, the structures of the conductive polymers and their composites can affect cytotoxicity and biocompatibility [103]. The form of protonation and deprotonation of the conductive polymers decreases cytotoxicity. Nevertheless, conductive polymers can be more toxic due to their insoluble nature and stability for a long time in an aqueous solution [104]. Therefore, the cytotoxicity aspect of conductive polymers and their nanocomposites with metal nanoparticles will need to be investigated thoroughly; a subject of future studies. Nevertheless, PANI and PPY offer several advantages including chemical stability, non-volatility, low toxicity, and very limited penetration into mammalian skin. For therapeutic applications, the materials must be subjected to its effect on red blood

cells, known as hemolysis with <4% hemolysis at the given MIC (minimum inhibition concentration) as a guideline [105]. Unfortunately, such information was not reported in numerous literary publications. The degree of hydrophobicity and cationic charge of polymers or polymer composites is crucial for attaining the best antibacterial activity with minimum red blood cells hemolysis [106]. Again, this important issue was completely missing from the literature publication. Direct evidence for the binding of antimicrobial polymers and bacterial membranes can be probed by scanning or transmission electron microscopy (SEM and TEM). FTIR also provides the fingerprinting of polymers [107] or nanoparticles [108] before and after their binding to a target bacterium. Other tools include Raman spectroscopy, atomic force microscopy (AFM), mass spectrometry, nuclear magnetic resonance spectroscopy, and X-ray photoelectron spectroscopy.

The production of ROS (very short life) can be detected by electron paramagnetic resonance (EPR) together with spin traps or spin probes to provide sufficiently long-lived and detectable radical adducts. Detection of ROS is also feasible using fluorescein-based stainings such as hydroxyphenylfluorescein and 2′,7′-dichlorodihydrofluorescein diacetate. However, the applicability of these two dyes has been a subject of debate [109].

7. Future Studies and Endeavors

Albeit a plethora of polymers and their composites have been reported in the literature, their potential replacement of existing antibiotics is far from certain as they must fulfill the following requirements.

- **A complete list of priority pathogens**. They must be tested against several pathogens, which are capable of "escaping" from common antibacterial treatments and have been listed as the World Health Organization (WHO) priority pathogens [110]: *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter* spp. Of importance is the eradication of *A. baumnannii*, which has been reported to be resistant to most known antibiotics, even colistin, the last resort of antibiotics. Besides its outer membrane being relatively impermeable, this bacterium is equipped with efflux pumps and produces beta-lactamases and biofilms to render multiple drugs ineffective. *K. pneumoniae* has developed resistance to almost all available antibiotics: fluoroquinolones, third-generation cephalosporins, and aminoglycosides. *Enterobacter* spp. and *P. aeruginosa* have become resistant to cephalosporins and carbapenems. *Enterococcus faecium* and *E. faecalis* have most frequently infected humans. Considering the emergence of multidrug-resistant bacteria and the lack of novel antibiotics, some discontinued toxic agents, e.g., colistin (polymyxin E), are recycled as the last "silver bullet" to kill multidrug-resistant bacteria [111]. Unfortunately, colistin-resistant bacteria have also emerged [112,113].
- **Biodegradable**. Controlled degradation of antimicrobial polymers is another prerequisite considering their plausible prolonged toxicity in human bodies or environments.
- **Hemolysis**. For treatment, conducting polymers must have low toxicity toward human erythrocytes with <4% hemolysis at the given MIC as a guideline as mentioned previously [98].
- **Competing technologies**. Dendrimers exhibit antimicrobial activities as they cause destabilization of the bacterial membrane structure. Dendrimers with multi-functional groups can be conjugated with existing antibiotics or peptides to augment their antimicrobial activities. An example is the antimicrobial activities of peptide dendrimer against multidrug-resistant *Acinetobactor baumanii* and *P. aeruginosa* [114]. Bacterial cellulose can be loaded with AgNPs for wound healing treatment [115]. Carboxylated nanocrystalline cellulose can be easily functionalized and decorated with AuNPs [116] as a platform for developing antimicrobial nanocomposites. A composite of chitosan-AuNPs shows high antibacterial activities with low cytotoxicity [117]. The surface of AuNPs can be functionalized with antimicrobial molecules, e.g., 6-aminopenicillanic

acid [118]. Albeit gold spheres are commonly used, gold rods and gold nanoparticles with other geometries remain to be tested [119].

Polyhexamethylene biguanide or polyhexanide is one of the most known antimicrobial polymers with low cytotoxicity, which can be synthesized from guanidine and hexylmethylenediamine [120]. This synthetic polymer exhibits broad-spectrum activity against bacteria and has diversified applications including wound dressings and as an antiseptic. Guanidine is a natural product with cationic properties [121] displaying interaction with the anionic counterpart, e.g., bacterial membranes. The chemistry and biology of guanidine and its derivatives can be found elsewhere [122].

Nevertheless, the development of antimicrobial polymers and polymer composites remains to be an active research area. Of considerable interest is the use of hydrogels with antimicrobial function. In brief, a hydrogel is a three-dimensional network of hydrophilic polymers with well-defined structures that can swell in water and hold a large amount of water. Hydrogels were first reported by Wichterle and Lím [123]. Antimicrobial hydrogels are also attractive materials for use as wound dressings and fillers. Due to their high water content, gels provide a moist, heavily hydrated environment to the wound area, facilitating cellular immunological activity essential to the wound healing process. The subject of antimicrobial hydrogels (pristine and loaded with drugs or nanoparticles) for the treatment of infection can be found elsewhere [124]. Magnetic hydrogels can be prepared from a mixture of human plasma and magnetic nanoparticles [125]. Ferrogels can also be prepared by radical polymerization of acrylamide in stabilized aqueous ferrofluid with different concentrations of magnetic nanoparticles [126]. Hydrogels might exhibit inherent antibacterial activities or are loaded with metal nanoparticles, antibiotics, biological extracts, etc., [127].

However, it is a long road to bring a potential product to "real world" applications as the product must be proven and validated to be effective at controlling infection with acceptable low cytotoxicity and hemolysis besides the cost issue. The antimicrobial mechanism must also be established to eradicate resistant bacteria that cannot be treated by available antibiotics. Albeit conducting polymers and their derivatives exhibit antimicrobial activities against fungi, yeasts, and bacteria, an exact mechanism remains to be elucidated. Nevertheless, electrostatic interactions between the protonated form of CPs and negatively charged bacterial cell walls are still considered an important initial step. Such interactions are also strengthened by van der Waals forces. The subsequent plausible insertion of CP components into the lipid domains of the microbial membrane form pores, facilitating the outflow of cytoplasm and other cellular components [128]. Doubtlessly, antimicrobial polymers must form composites with metal nanoparticles or are conjugated with natural small organic molecules with antimicrobial properties and low cytotoxicity. Such polymer composites with multimodal mechanisms of action can resist acquired resistance by the WHO priority bacteria.

8. Conclusions

The development of antimicrobial polymers for diversified applications is of great challenge for both academia and industries as pathogens infect medical devices, healthcare products, potable water, food packaging, food storage, etc. Low-cost antimicrobial polymers are needed to replace antimicrobial agents of low molecular weight for the decontamination of water, soil sterilization, and food packaging. They can be used for coating fresh vegetables and fruits to preserve freshness and fend off fungal degradation. Coating textiles and fibrous materials with antimicrobial polymers is another major application to protect textile materials from biodegradation. Besides medical devices, coating materials with antimicrobial properties also find several applications in clinical and hospital facilities such as operating tables, doors, walls, chairs, and other frequently touched objects. Such objects are often contaminated with *S. aureus*, *Acinetobacter*, *E. coli*, and *Pseudomonas*, which produce biofilms for their protection and survival. Consequently, antimicrobial materials are also needed for improved hand hygiene among patients, healthcare workers, and visitors.

Essentially, a broad antimicrobial spectrum is observed for most pathogens with unequivocal dose-dependent growth inhibition. However, the MICs (minimum inhibition concentrations) of CPs are considerably higher than those of antibiotics. Enhanced antimicrobial properties can be achieved by functionalized carbon dots (*f*-CDs), copolymers, and polymer nanocomposites with metal oxides or small molecules. The CDs-initiated polymers are chelated with metallic nanoparticles, broadly defined as nanoparticles of metals, by ultra-sonication to impart enhanced antimicrobial properties against sensitive and antibiotic-resistant bacteria. Their antimicrobial properties as well as plausible caveats such as cytotoxicity, low efficacy, and induction of antimicrobial resistance remain to be elucidated. Future studies could focus on conducting polymers and their composites that can be formulated with antibiotics and other natural products with robust antimicrobial properties. The antimicrobial mechanism must also be established to eradicate resistant bacteria that cannot be treated by available antibiotics. This research field requires an interdisciplinary team encompassing chemists, material scientists, microbiologists, and clinicians. The functionalization of conducting polymers with nanoparticles, antibiotics, antibodies, etc., also plays an important role in biosensing, bacteria sensing, bacteria sorting and concentration, chromatography, medical imaging, drug delivery, and other important applications.

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