Quorum quenching nanoparticles against wound pathogens – A scoping review

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ABSTRACT

Introduction: Quorum sensing (QS) enables bacteria to coordinate colony-wide activities, including those associated with infections. Quorum quenching (QQ) inhibits QS and is a promising method for controlling bacterial infections. Several In vitro experiments have been conducted to identify nanoparticles (NPs) as potential quorum quenching inhibitors. This review examines the potential of nanoparticles for quorum quenching, focusing on the QS-regulated pathogenicity of wound pathogens.

Materials and Methods: Observational studies were conducted to explore the capacity of nanoparticles to quorum quench wound pathogens.

Results: A review of observational studies indicated that nanoparticles exhibit significant quorum-quenching capabilities against wound pathogens. Numerous nanoparticles, including silver, gold, and zinc oxide, have been demonstrated to inhibit QS-regulated activities, thereby reducing bacterial virulence and biofilm formation. These results suggest that nanoparticles could serve as potent agents for mitigating bacterial infections and enhancing wound healing.

Conclusion: Nanoparticles show considerable potential as quorum-quenching agents, effectively decreasing bacterial virulence and biofilm formation in wound pathogens. These results indicate promising applications of nanoparticles in managing bacterial infections and improving wound healing.

KEYWORDS:
Quorum sensing, Quorum quenching, Wound pathogens, Nanoparticles

INTRODUCTION

Bacterial cells have the capacity to communicate with one another by producing and detecting extracellular chemicals (autoinducers) that can passively or actively pass through cell membranes, which is called quorum sensing (QS).[1] Consequently, the bacterial population can synchronize the expression of several genes to enable a simultaneous response. When their concentration reaches a particular threshold, autoinducers (AI) engage with transcriptional regulators within bacteria possessing the QS system, resulting in alterations to genetic expression patterns.[2] A greater number of genes were turned on or off when a specific cell density was attained. Furthermore, autoinducers attach to the extracellular segments of histidine kinase membrane receptors, initiating autophosphorylation and eliciting a corresponding cytoplasmic response.[3] Gram-positive and Gram-negative bacteria exhibit distinct QS systems, mainly due to the chemical composition of their autoinducers. L-homoserine lactones (HSLs), which generally, but not exclusively, diffuse passively across the cell membrane, are utilized by gram-negative bacteria, whereas gram-positive organisms predominantly employ autoinducing peptides for transportation.[4] The investigation of quorum sensing inhibitors has emerged as a highly intriguing field in antimicrobial research.[5] Antimicrobial compounds that target the virulence mechanisms in various bacteria by inhibiting quorum sensing have emerged as a new class of drugs. The exploration of QS inhibitors appears as one of the Quorum Quenching (QQ) strategies has been suggested to obstruct quorum sensing. These approaches involve eliminating or breaking down signaling molecules, hindering their production, impeding the formation of signaling molecules and receptor complexes, and thwarting the binding of signal transduction cascades.[6]

Every open wound has bacteria from endogenous or exogenous sources because of the absence of a protective barrier in the skin. The host immune system usually keeps these microorganisms in check or removes them during the initial phases of chronic wound formation. However, if the bacteria adhere to the wound surface and proliferate, they initiate biofilm formation.[7] Once a biofilm is firmly formed, neither the host's immune system nor antimicrobial medications will be effective in eradicating it. The biofilm is considered to be developed and more challenging to remove at this point, and the wound will be infected by the biofilm.[8] In these circumstances, there is a greater chance that a wound will not heal and will develop as an open clinical infection (i.e., symptoms of inflammation or purulence). Therefore, preventing biofilm formation in the early stages is essential to expedite and improve the healing process of chronic wounds.[9]

The utilization of nanotechnology in agriculture, therapeutics, diagnostics, and other fields has gained significant attention owing to recent advancements.[10] Drug resistance has been growing steadily and has challenged the scientific community to develop better antibacterial drugs. Metal nanoparticles (NPs) have been proven to function as powerful antibacterial agents. Antibacterial NPs are thought

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to have the potential to target multiple biomolecules simultaneously, thereby minimizing the chance of antibiotic resistance and developing drug-resistant strains.[11] Antimicrobial nanoparticles have been linked to several mechanisms, including free metal ion toxicity caused by metals breaking off the nanoparticle surfaces and oxidative damage triggered by reactive oxygen species (ROS) generated on these surfaces.[12] Bacteria show membrane damage as a result of the adsorption and subsequent penetration of nanoparticles into their cells. By changing the cell wall's usual negative charge, NPs adsorption causes depolarization, which increases the permeability of the wall.[13] This review investigates the potential of nanoparticles against quorum sensing in wound pathogens, thereby inhibiting their virulence and biofilm formation.

MATERIALS AND METHODS

Protocol and Sources of Information

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRSIMA-ScR). The study material consisted of articles on the quorum-quenching activity of nanoparticles on wound pathogens, published before June 1, 2022. These articles were sourced from PubMed database.

Eligibility Criteria

We included primary In vitro studies published in English to evaluate the relationship between the use of nanoparticles and antimicrobial activity against the most prevalent microorganisms associated with wound infections, such as *P. aeruginosa, S. aureus, E. coli, K. pneumonia*, and other pathogens. There were no restrictions on the publication date or study location.

Data Charting Process

Both authors (J.A. and R.S.) performed data extraction. They utilized a pre-defined Excel form to gather the following information from each article: study identification details, study type, study objective, quorum sensing ability of wound pathogens, and the effectiveness of various nanoparticles against wound pathogens (In vitro).

Inclusion and exclusion criteria:

The inclusion criteria were articles reporting studies that used nanoparticles to act against wound pathogens and provided information about the quorum sensing ability of these pathogens. Meanwhile, the extension criteria consisted of articles that could not be accessed in the full text, were in non-English languages, or were not original research.

RESULTS

Searches were conducted between June and September 2023, and updated in January 2024. Database searches identified 273 manuscripts from 2001 to 2022. Figure 1 shows a PRISMA flowchart detailing the search and selection processes. After removing eight duplicates, 265 manuscripts were selected for the initial screening. Articles without full-text availability or those falling outside the inclusion criteria (wound pathogens) were analyzed, resulting in the exclusion of 238 articles. Articles were excluded based on their titles and abstract relevance. Ultimately, 23 articles were assessed for eligibility and included in this review, while 4 manuscripts were excluded due to accessibility issues. The frequency of publications has increased recently, reflecting growing interest in the field.

QUORUM-SENSING WOUND PATHOGENS

Bacterial biofilm on the wound is a thin layer caused by a cluster of bacteria attached to the surface of the wound, which is caused by both gram-negative and gram-positive bacteria, such as Escherichia coli, *Staphylococcus aureus, Pseudomonas aeruginosa, Staphylococcus epidermidis, Enterococcus faecalis, Klebsiella pneumonia* and other pathogens.

Pseudomonas aeruginosa is a notable human disease-causing organism that mostly affects individuals with cystic fibrosis (CF), cancer, and organ transplant recipients. It can also be detected in burns and cutaneous bruises.[14] The three Quorum Sensing circuits in this bacterium are active. One of these circuits is controlled by hormone-sensitive lipase (HSLs) and includes the genes LasR transcriptional activators-lasR and lasI, the genes responsible for producing the autoinducer (N-3-oxo-dodecanopyl)-L-homoserine lactone, which is essential for this circuit's signaling. The second circuit, also regulated by homoserine lactone, comprises the rhlI gene, rhlR gene encoding the transcriptional activator RhlR, and an enzyme responsible for the production of the N-(butanoyl)-L-homoserine lactone autoinducer.[15] The compound 2-heptyl-3-hydroxy-4-quinolone is synthesized by the products of the pqsABCDEH genes and is regulated by the PqsR regulator16. The regulatory hierarchy for all three systems involves LasR positively regulating RhlR, whereas RhlR exerts a negative regulatory influence on PQS.[17]

The significance of QS in human diseases associated with *P. aeruginosa* has been well established. According to numerous investigations, 90 percent of *P. aeruginosa* samples that can cause infections have working HSL systems. In one instance, it has been demonstrated that patients with cystic fibrosis typically have N-(3-oxododecanoyl)-HSL, the major *P. aeruginosa* auto inducer.[18] Polysaccharide alginate, a crucial part of the matrix created by *P. aeruginosa* strains, is a QS-controlled virulence factor that shields biofilms from macrophage destruction.[19]

Gram-positive *Staphylococcus aureus* is a non-motile coccus that produces a yellow pigment and clusters of cells. Numerous illnesses, including bacteremia, endocarditis, sepsis, and infections of the epidermis and various other tissues, are brought on by this bacterium.[20] *S. aureus* aids in infections caused by the synthesis of an extensive array of virulence factors, including enzymes, exotoxins, and adhesins.[21] A significant portion of these virulence factors is regulated by Agr system, which is an accessory gene regulator dependent on quorum sensing.[22]

The RNAII transcript and hld gene consist of genes located within the AGR locus, namely agrA, agrC, agrD, and agrB. The pro-peptide AgrD undergoes conversion into auto

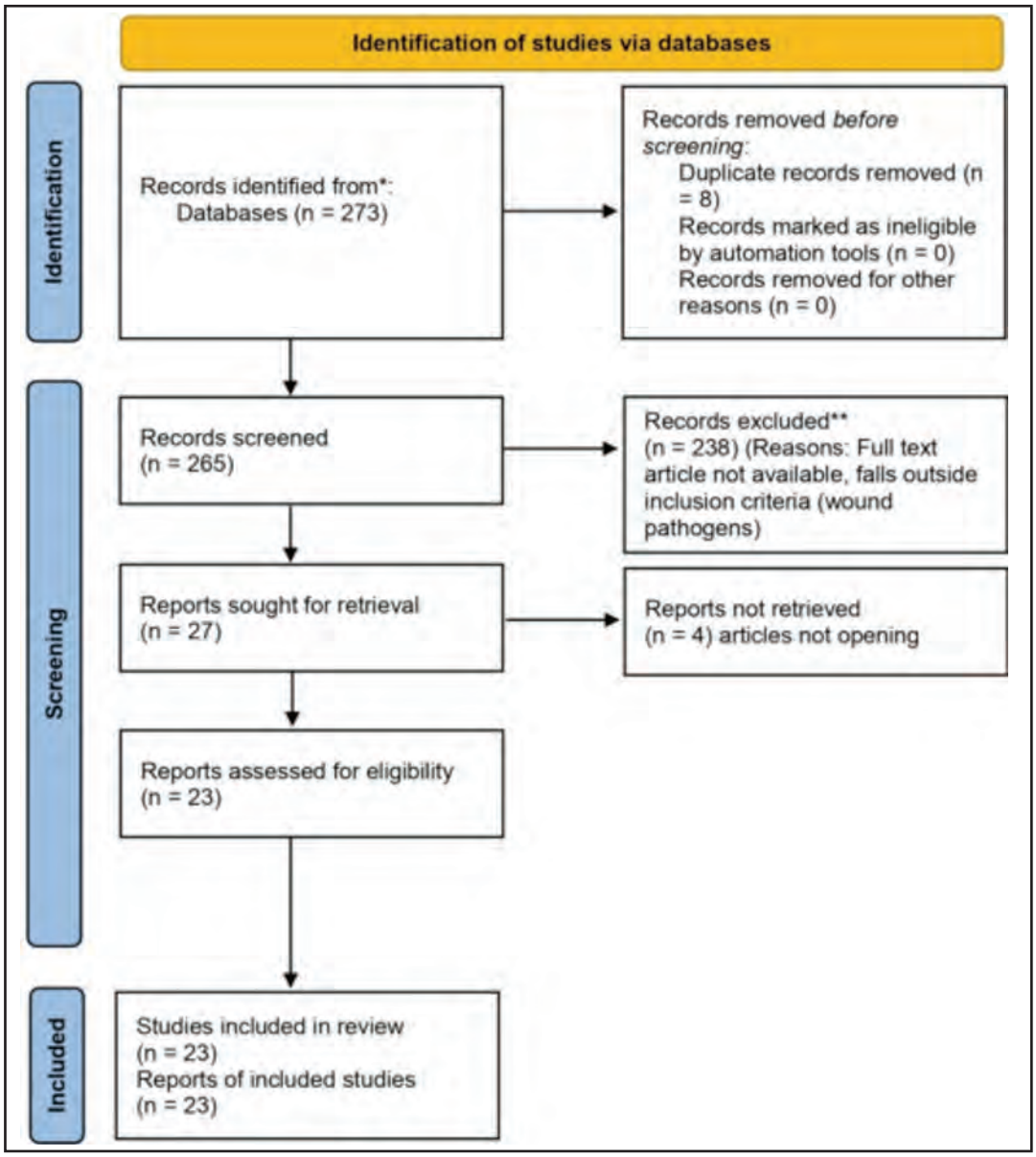

Fig. 1: Flow chart for the scoping review process

inducing peptides (AIPs). This conversion occurs through the export and processing of the pheromone AgrD, which is facilitated by AgrB and SpsB peptidase.[23] These peptides vary in length, typically spanning seven to nine amino acids, but they share a common feature: a thiolactone ring located at their C-terminus.[24] The *S. aureus* hld gene of *S. aureus* produces an RNAIII effector molecule that post-transcriptionally controls many virulence factors.[25,26] RNAIII is responsible for regulating biofilm production by *Staphylococcus aureus*. Because of its limited motility, this bacterium forms flatter biofilms than genera that exhibit greater mobility.[27] Teichoic acid-based glycocalyx or slime is incorporated into the *S. aureus* biofilm.[28] In addition to the previously mentioned factors, polysaccharide intercellular antigen (PIA) and extracellular DNA (eDNA) are significant components of biofilms. These substances are produced as a result of extensive cell lysis, facilitated by the holing homolog CidA, and contribute to the formation and stability of biofilms.[29]

Klebsiella pneumonia is a gram-negative bacterium known for its ability to induce various infections, including urinary tract infections, pneumonia, wound infections, surgical site infections, meningitis, and intra-abdominal infections. The synthesis of AI-2 (autoinducer-2) in non-motile or sessile *Klebsiella pneumonia* cells appears to function as a regulator of biofilm formation and the production of lipopolysaccharides (LPS) 30. The process of quorum sensing among wound pathogens occurs as depicted in figure 2.

QUORUM QUENCHING NANOPARTICLES

Nanoparticles can serve as excellent quorum quenchers, offering an excellent solution due to their unique physicochemical properties that allow them to interact with bacterial cells. Specifically, metal and metal oxide nanoparticles (such as silver, zinc oxide, and titanium dioxide) can attach to bacterial cell membranes, causing

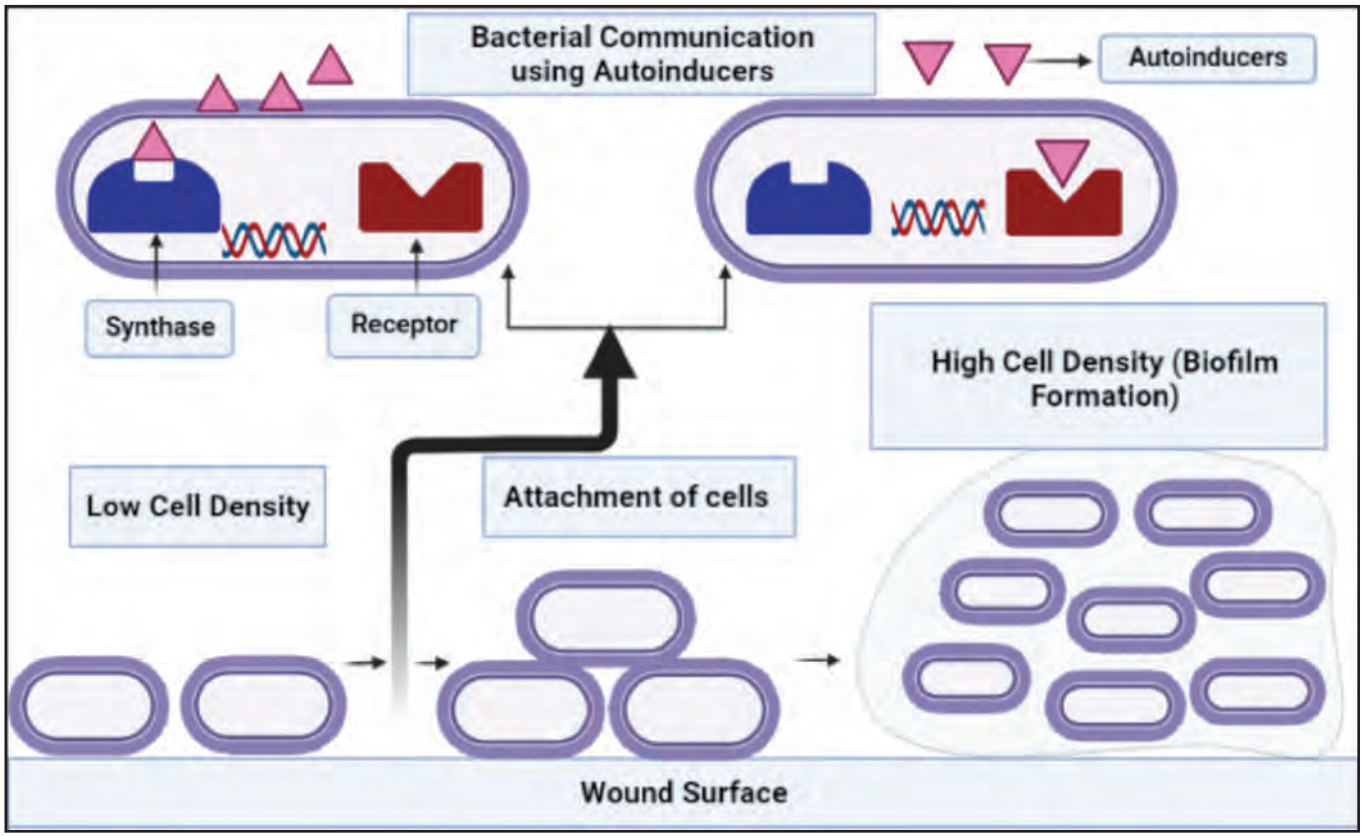

Fig. 2: Quorum sensing of wound pathogens

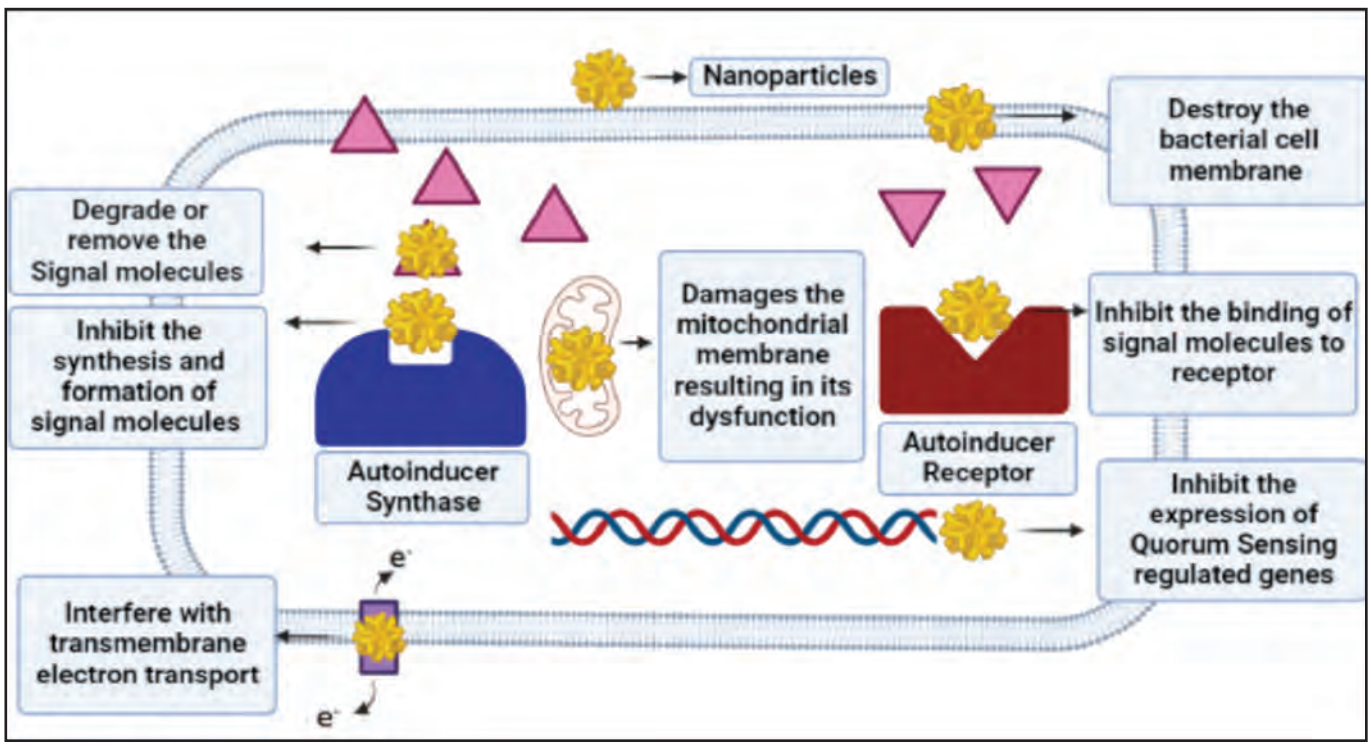

Fig. 3: Quorum Quenching Efficacy of Nanoparticles

Table I: Studies that displays the Quorum quenching ability of different nanoparticles:

First author	Publication year	Type of nanoparticles	Outcomes
Jagtap S[31]	2013	Silver nanowires	Inhibited the biofilm growth of *P. aeruginosa*
Bamal D[32]	2021	Silver nanoparticles (AgNPs)	Exhibited bactericidal activity against *Proteus mirabilis, Staphylococcus aureus*, and *Pseudomonas aeruginosa*
Kalishwarlal[33]	2010	AgNPs	Hindered the first phase of bacterial adherence of *P. aeruginosa* and *Staphylococcus epidermidis* to the colonized surface
Martinez-Gutierrez F[34]	2013	AgNPs	Destroyed the biofilm produced by *P. aeruginosa*
Mohanta YK[35]	2010	AgNPs	Effectively lower the initial stages of *P. aeruginosa* biofilm formation by restricting bacterial attachment to the polystyrene surfaces
Xu L[36]	2020	Startch stabilized AgNPs	Disrupted the biofilms of *P. aeruginosa* and *S. aureus*
Masurkar SA[37]	2012	Cymbopogan citratus leaf extract AgNPs	Inhibited biofilm formation by *S. aureus*
Qais FA[38]	2018	AgNPs	Suppressed the gene expression of PAO1 virulence genes of *P. aeruginosa*
Lamin A[39]	2022	AgNPs	Suppressed the expression of genes - lasA, lasB, phzA1, and rhlA in the planktonic cells of *P. aeruginosa* (PAO1)
Shin D[40]	2019	AgNPs	Significantly reduced the production of C12-AHL (Acyl homoserine lactones) and C4-AHL
Wagh MS[41]	2013	Silver nanowires	Effectively suppressed biofilm formed by *P. aeruginosa*
Chaudhari[42]	2015	PEGlyted silver coated carbon nanotubes	Decreased the expression of virulence genes safC, ychP, sseA, sseG, and even sdiA (a quorum sensing gene) in *S. aureus*
Sathyanarayanan MB[45]	2013	Gold nanoparticles (AuNPs)	Significantly reduced the biofilms of S. aureus and P. aeruginosa
Samanta S[46]	2017	Laccaria fraterna mycelium mediated AuNPs	Significantly inhibited *P. aeruginosa* pyocyanin synthesis and QS-regulated biofilm formation
García-Lara B[47]	2015	Zinc oxide nanoparticles (ZnONPs)	ZnONPs provides several options for combating against *P. aeruginosa* infections that are multi-drug resistant
Al-Shabib NA[48]	2018	Ochradenus baccatus leaves mediated ZnONPs	Suppressed QS-regulated biofilm formation in *P. aeruginosa, E. coli,* and many other bacteria.
Al-Shabib NA[49]	2016	Nigella sativa mediated ZnONPs	Down regulated the lasB gene, resulting in a subsequent reduction in the production of AHLs
Liao C[50]	2020	UV radiation exposed titanium dioxide nanoparticles (TiO_2NPs)	Efficiently inhibited the proliferation of methicillin-resistant *S. aureus*
Cho KH[51]	2005	TiO_2NPs	Showed influence on the expression of QS and efflux pump genes in multi-drug resistant *P. aeruginosa* strains
Ahmed FY[52]	2021	*Aloe barbadensis* mediated TiO_2NPs	Reduced the cell viability of *P. aeruginosa* biofilm
Rajkumari J[53,54]	2019	Chitosan nanoparticles	Blocked the migration of AHLs into the cytoplasm and inhibited AI synthase in *E. coli*
Subhaswaraj[55]	2018	Cinnamaldehyde-encapsulated chitosan nanoparticles	Inhibited the virulence factors and biofilms in *P. aeruginosa* PAO1 strain.

structural damage and increased permeability. This attachment leads to the leakage of cellular content and eventual cell death. Additionally, nanoparticles can penetrate biofilms and disrupt their structural integrity, thereby inhibiting quorum sensing and reducing bacterial communication and virulence. Studies on the QQ ability of different nanoparticles are summarized in Table I.

DISCUSSION

Quorum sensing (QS) plays a crucial role in the pathogenesis and persistence of wound infections caused by various bacterial species. QS-regulated production of factors, such as exopolysaccharides, can inhibit phagocytosis and other immune responses, allowing bacteria to evade destruction by the immune system of the host.[56] The presence of quorum-sensing bacteria in wounds can delay the healing process by maintaining chronic inflammation and tissue damage. Moreover, QS can interfere with the efficacy of conventional antimicrobial treatments by promoting biofilm formation and increasing resistance, necessitating the development of alternative therapeutic strategies to target QS pathways.[57]

Nanoparticles can serve as outstanding quorum quenchers by targeting biofilms formed by wound pathogens and multidrug-resistant bacteria. Nanoparticles can penetrate biofilms and disrupt their structural integrity, which is particularly important because biofilms protect bacteria from

antibiotics and the host immune system, contributing to chronic infections.[58] Additionally, nanoparticles can be incorporated into wound dressings, gels, and ointments for direct application to infected wounds, providing continuous antimicrobial action and promoting faster healing.[59]

Mohanta YK et al. (2010) showed that AgNPs with sizes ranging from 1 to 10 nm, applied at a concentration of 4 g mL-1, effectively lowered the initial stages of *P. aeruginosa* biofilm formation by restricting bacterial attachment to polystyrene surfaces. In addition to reducing cell viability within the biofilm and inducing morphological changes such as cytoplasmic condensation, it was also demonstrated that the production of biofilm matrix components was diminished.[35]

Researchers have been giving a lot of attention to gold nanoparticles (AuNPs) in both fundamental and applied research. AuNPs have extensive applications in biology and diagnostics and function as catalysts for diverse purposes. One of the primary advantages of AuNPs is their simple chemical reduction method of synthesis and comparatively low toxicity compared to other nanomaterials.[43] They exhibit antibacterial activity against several organisms including methicillin-resistant organisms.[44]

Zinc oxide nanoparticles (ZnONPs) diminish the virulence factors of *P. aeruginosa* and biofilm development in animal models, resulting in fewer infections. Nevertheless, research involving clinical or environmental isolates is rare, and they are often conducted using laboratory strains such as PAO1 and PA14. The study conducted by García-Lara B et al. (2015) examined the impact of ZnONPs, known for their potency in quorum and virulence quenching of the PAO1 strain, on six clinical strains from cystic fibrosis patients, a clinical strain from urine that was resistant to furanone C-30, two mutants of PA14 that were gallium-resistant, one mutant that was resistant to PA14 C-30, and four environmental isolates. For most strains, ZnONPs efficiently reduced the formation of elastase, pyocyanin, and biofilms, independent of their origin or resistance to the traditional quorum quencher C-30 or cutting-edge antibacterial gallium. According to research findings, ZnONPs could offer different options for treating *P. aeruginosa* infections that are resistant to treatment because of their potential broad-spectrum quorum quenching activity against relevant strains.[47]

The influence of TiO2NPs on the expression of QS and efflux pump genes in multi-drug-resistant *P. aeruginosa* isolates was also examined. The investigation revealed that TiO2NPs exhibited enhanced antibacterial action against *P. aeruginosa* strains compared with TiO_2 powder, resulting in a significant 96% reduction in biofilm production. Additionally, the application of TiO_2NPs, either alone or in conjugation with antibiotics, significantly reduced the expression of key efflux pump genes (MexY, MexB, and MexA) and genes regulated by (lasR, lasI, rhll, rhlR, pqsA, and pqsR). This suggests that TiO_2NPs can influence the expression of the efflux pump and quorum-sensing genes that regulate biofilm formation, enhancing the therapeutic effectiveness of conventional antibiotics.[51]

Chitosan nanoparticles offer a means to enhance the quorum sensing inhibitory effects of various antimicrobial drugs. Chitosan and its derivatives can be used to encapsulate phytochemicals, thereby increasing their Anti-quorum sensing (Anti-QS) effects. For instance, compared to their free forms, the encapsulation of flavonoids like baicalein and quercetin enhanced their QQ potential against the *E. coli* sensors when compared to their free forms. The quorum quenching mechanism of these flavonoid-loaded nanocapsules involves either blocking the migration of AHLs into the cytoplasm or inhibiting AI synthase. Non-toxic chitosan also demonstrated QQ action in *E. coli* and caused cell aggregation at low doses. Cell aggregation suggests that QS is inhibited by slowing the diffusion of AHLs.[53,54] The quorum quenching capability of the NPs to inhibit QS and destroy bacterial cells is illustrated in figure 3.

CONCLUSIONS

An efficient alternative approach for treating microbial infections is interference with Quorum Sensing is Quorum Quenching. Nanoparticles exhibiting anti-quorum sensing (anti-QS) properties act as potential antibacterial agents against bacterial infections, especially in the current scenario, where the sustained effectiveness of antibiotics is uncertain. Nanoparticles have emerged as a novel category of antibacterial agents and carriers for drug delivery owing to their exceptional physicochemical properties, diminutive size, and substantial surface area-to-volume ratio. The capacity of nanoparticles to inhibit QS suggests that they have a good chance of successfully treating infections caused by bacterial biofilms. For clinical use, it will be extremely beneficial to fully understand the mechanism underlying QQ action and, consequently, the way in which NPs interfere with bacterial virulence. At present, there is a dearth of information regarding the ecotoxicities and clinical applications of nanoparticles. Before nanoparticles receive approval for widespread clinical use, comprehensive research is imperative to elucidate both their positive and negative impacts.

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REFERENCES

1. Garg N, Manchanda G, Kumar A. Bacterial quorum sensing: circuits and applications. Antonie Van Leeuwenhoek 2014; 105: 289-305.
2. Zhang W, Li C. Exploiting quorum sensing interfering strategies in gram-negative bacteria for the enhancement of environmental applications. Front. microbiol. 2016; 6: 1535.
3. Ke X, Miller LC, Bassler BL. Determinants governing ligand specificity of the V ibrio harveyi L ux N quorum-sensing receptor. Mol Microbiol 2015; 95(1): 127-42.
4. LaSarre B, Federle MJ. Exploiting quorum sensing to confuse bacterial pathogens. Microbiol Mol Biol Rev 2013; 77(1): 73-111.
5. Nandi S. Recent advances in ligand and structure based screening of potent quorum sensing inhibitors against antibiotic resistance induced bacterial virulence. Recent Pat Biotechnol 2016; 10(2): 195-216.

6. Wolska KI, Grudniak AM, Markowska K. Inhibition of bacterial quorum sensing systems by metal nanoparticles. Metal Nanoparticles in Pharma 2017: 123-38.
7. Percival SL, McCarty SM, Lipsky B. Biofilms and wounds: an overview of the evidence. Adv Wound Care. 2015; 4(7): 373-81.
8. Wolcott RD, Rhoads DD, Bennett ME, Wolcott BM, Gogokhia L, Costerton JW, Dowd SE. Chronic wounds and the medical biofilm paradigm. J Wound Care 2010; 19(2): 45-53.
9. Pg B. Wound microbiology and associated approaches to wound management. Clin Microbiol Rev 2001; 14: 244-69.
10. Valcárcel J, Ortín J. Viral cell biology: Influenza raids the splicing store. Nat Microbiol. 2016 Jun 24;1(7):1-2.
11. Slavin YN, Asnis J, Hńfeli UO, Bach H. Metal nanoparticles: understanding the mechanisms behind antibacterial activity. J Nanobiotechnology 201715: 1-20.
12. Besinis A, De Peralta T, Handy RD. The antibacterial effects of silver, titanium dioxide and silica dioxide nanoparticles compared to the dental disinfectant chlorhexidine on Streptococcus mutans using a suite of bioassays. Nanotoxicology. 2014; 8(1): 1-6.
13. Leung YH, Ng AM, Xu X, Shen Z, Gethings LA, Wong MT, Chan CM, Guo MY, Ng YH, Djurišić AB, Lee PK. Mechanisms of antibacterial activity of MgO: non-ROS mediated toxicity of MgO nanoparticles towards Escherichia coli. Small. 2014; 10(6): 1171-83.
14. Ammons MC, Ward LS, Fisher ST, Wolcott RD, James GA. In vitro susceptibility of established biofilms composed of a clinical wound isolate of Pseudomonas aeruginosa treated with lactoferrin and xylitol. Int J Antimicrob Agents. 2009; 33(3): 230-6.
15. Steindler L, Bertani I, De Sordi L, Schwager S, Eberl L, Venturi V. LasI/R and RhlI/R quorum sensing in a strain of Pseudomonas aeruginosa beneficial to plants. Appl Environ Microbiol. 2009; 75(15): 5131-40.
16. Rather MA, Saha D, Bhuyan S, Jha AN, Mandal M. Quorum quenching: A drug discovery approach against Pseudomonas aeruginosa. Microbiol Res 2022 Aug 23: 127173.
17. Soto-Aceves MP, Cocotl-Yañez M, Servín-González L, Soberón-Chávez G. The Rhl quorum-sensing system is at the top of the regulatory hierarchy under phosphate-limiting conditions in Pseudomonas aeruginosa PAO1. J Bacteriol 2021; 203(5): 10-128.
18. Moradali MF, Ghods S, Rehm BH. Pseudomonas aeruginosa lifestyle: a paradigm for adaptation, survival, and persistence. Front cell infect microbiol 2017; 7: 39.
19. Skariyachan S, Sridhar VS, Packirisamy S, Kumargowda ST, Challapilli SB. Recent perspectives on the molecular basis of biofilm formation by Pseudomonas aeruginosa and approaches for treatment and biofilm dispersal. Folia Microbiol 2018; 63: 413-32.
20. Taj Z, Chattopadhyay I. Staphylococcus aureus Virulence Factors and Biofilm Components: Synthesis, Structure, Function and Inhibitors. InESKAPE Pathogens: Detection, Mechanisms and Treatment Strategies 2024 Mar 30 (pp. 227-270). Singapore: Springer Nature Singapore.
21. Cheung GY, Bae JS, Otto M. Pathogenicity and virulence of Staphylococcus aureus. Virulence. 2021 Dec 31;12(1):547-69.
22. Singh R, Ray P. Quorum sensing-mediated regulation of staphylococcal virulence and antibiotic resistance. Future Microbiol 2014; 9(5): 669-81.
23. Zhao A. Studies of the Biosynthesis, Signaling, and Manipulation of the Staphylococcal Agr Quorum Sensing Circuit (Doctoral dissertation, Princeton University).
24. Lyon GJ, Novick RP. Peptide signaling in Staphylococcus aureus and other Gram-positive bacteria. Peptides 2004; 25(9): 1389-403.
25. Fechter P, Caldelari I, Lioliou E, Romby P. Novel aspects of RNA regulation in Staphylococcus aureus. FEBS Lett 2014; 588(15): 2523-9.
26. Winn M. Expanding the biocatalytic toolkit: utilising biofilms as an adaptable biocatalytic platform and the development of a general, regioselective pyrrole halogenase (Doctoral dissertation, University of East Anglia).
27. Stoodley P, Hall-Stoodley L, Costerton B, DeMeo P, Shirtliff M, Gawalt E, Kathju S. Biofilms, biomaterials, and device-related infections. InHandbook of polymer applications in medicine and medical devices 2013 Jan 1 (pp. 77-101). William Andrew Publishing.
28. Husain Fm, Ahmad I, Asif M, Tahseen Q. Influence of clove oil on certain quorum-sensing-regulated functions. J Biosci 2013; 38(5): 1-0.
29. Wolska KI, Grudniak AM, Markowska K, 2016. Inhibitors of bacterial quorum sensing systems and their role as potential therapeutics. Postepy Mikrobiologii, 55(3): 300-308.
30. Sun S, Zhang H, Lu S, Lai C, Liu H, Zhu H. The metabolic flux regulation of Klebsiella pneumoniae based on quorum sensing system. Sci. Rep 2016; 6(1): 38725.
31. Jagtap S, Priolkar KR. Evaluation of ZnO nanoparticles and study of ZnO–TiO2 composites for lead free humidity sensors. Sensor Actuat B-Chem. 2013; 183: 411-8.
32. Bamal D, Singh A, Chaudhary G, Kumar M, Singh M, Rani N, Mundlia P, Sehrawat AR. Silver nanoparticles biosynthesis, characterization, antimicrobial activities, applications, cytotoxicity and safety issues: An updated review. Nanomaterials 2021; 11(8): 2086.
33. Kalishwaralal K, BarathManiKanth S, Pandian SR, Deepak V, Gurunathan S. Silver nanoparticles impede the biofilm formation by Pseudomonas aeruginosa and Staphylococcus epidermidis. Colloids Surf B Biointerfaces 2010; 79(2): 340-4.
34. Martinez-Gutierrez F, Boegli L, Agostinho A, Sánchez EM, Bach H, Ruiz F, James G. Anti-biofilm activity of silver nanoparticles against different microorganisms. Biofouling. 2013; 29(6): 651-60.
35. Mohanta YK, Biswas K, Jena SK, Hashem A, Abd_Allah EF, Mohanta TK. Anti-biofilm and antibacterial activities of silver nanoparticles synthesized by the reducing activity of phytoconstituents present in the Indian medicinal plants. Front microbiol 2020; 11: 1143.
36. Xu L, Wang YY, Huang J, Chen CY, Wang ZX, Xie H. Silver nanoparticles: Synthesis, medical applications and biosafety. Theranostics 2020; 10(20): 8996.
37. Masurkar SA, Chaudhari PR, Shidore VB, Kamble SP. Effect of biologically synthesised silver nanoparticles on Staphylococcus aureus biofilm quenching and prevention of biofilm formation. IET nanobiotechnol 2012; 6(3): 110-4.
38. Qais FA, Khan MS, Ahmad I. Nanoparticles as quorum sensing inhibitor: Prospects and limitations. Biotechnological applications of quorum sensing inhibitors. 2018: 227-44.
39. Lamin A, Kaksonen AH, Cole IS, Chen XB. Quorum sensing inhibitors applications: A new prospect for mitigation of microbiologically influenced corrosion. Bioelectrochemistry. 2022; 145: 108050.
40. Shin D, Gorgulla C, Boursier ME, Rexrode N, Brown EC, Arthanari H, Blackwell HE, Nagarajan R. N-acyl homoserine lactone analog modulators of the Pseudomonas aeruginosa Rhll quorum sensing signal synthase. ACS Chem. Biol 2019; 14(10): 2305-14.
41. Wagh MS, Patil RH, Thombre DK, Kulkarni MV, Gade WN, Kale BB. Evaluation of anti-quorum sensing activity of silver nanowires. Appl Microbiol Biotechnol 2013; 97: 3593-601.
42. Chaudhari AA, Jasper SL, Dosunmu E, Miller ME, Arnold RD, Singh SR, Pillai S. Novel pegylated silver coated carbon nanotubes kill Salmonella but they are non-toxic to eukaryotic cells. J Nanobiotechnology 2015; 13(1): 1-7.
43. Yeh YC, Creran B, Rotello VM. Gold nanoparticles: preparation, properties, and applications in bionanotechnology. Nanoscale 2012; 4(6): 1871-80.
44. Mobed A, Hasanzadeh M, Seidi F. Anti-bacterial activity of gold nanocomposites as a new nanomaterial weapon to combat photogenic agents: Recent advances and challenges. RSC Adv 2021; 11(55): 34688-98.

45. Sathyanarayanan MB, Balachandranath R, Genji Srinivasulu Y, Kannaiyan SK, Subbiahdoss G. The effect of gold and iron-oxide nanoparticles on biofilm-forming pathogens. Int Sch Res Notices 2013; 2013.
46. Samanta S, Singh BR, Adholeya A. Intracellular synthesis of gold nanoparticles using an ectomycorrhizal strain EM-1083 of Laccaria fraterna and its nanoanti-quorum sensing potential against Pseudomonas aeruginosa. Indian J Microbiol 2017; 57: 448-60.
47. García-Lara B, Saucedo-Mora MÁ, Roldán-Sánchez JA, Pérez-Eretza B, Ramasamy M, Lee J, Coria-Jimenez R, Tapia M, Varela-Guerrero V, García-Contreras R. Inhibition of quorum-sensing-dependent virulence factors and biofilm formation of clinical and environmental Pseudomonas aeruginosa strains by ZnO nanoparticles. Lett Appl Microbiol 2015; 61(3): 299-305.
48. Al-Shabib NA, Husain FM, Hassan I, Khan MS, Ahmed F, Qais FA, Oves M, Rahman M, Khan RA, Khan A, Hussain A. Biofabrication of Zinc Oxide Nanoparticle fromOchradenus baccatusLeaves: Broad-Spectrum Antibiofilm Activity, Protein Binding Studies, and In VivoToxicity and Stress Studies. J Nanomater 2018; 2018: 1-4.
49. Al-Shabib NA, Husain FM, Ahmed F, Khan RA, Ahmad I, Alsharaeh E, Khan MS, Hussain A, Rehman MT, Yusuf M, Hassan I. Biogenic synthesis of Zinc oxide nanostructures from Nigella sativa seed: Prospective role as food packaging material inhibiting broad-spectrum quorum sensing and biofilm. Scientific reports 2016; 6(1): 36761.
50. Liao C, Li Y, Tjong SC. Visible-light active titanium dioxide nanomaterials with bactericidal properties. Nanomaterials. 2020 Jan 9;10(1):124.
51. Ahmed FY, Aly UF, Abd El-Baky RM, Waly NG. Effect of titanium dioxide nanoparticles on the expression of efflux pump and quorum-sensing genes in MDR Pseudomonas aeruginosa isolates. Antibiotics 2021; 10(6): 625.
52. Rajkumari J, Magdalane CM, Siddhardha B, Madhavan J, Ramalingam G, Al-Dhabi NA, Arasu MV, Ghilan AK, Duraipandiayan V, Kaviyarasu K. Synthesis of titanium oxide nanoparticles using Aloe barbadensis mill and evaluation of its antibiofilm potential against Pseudomonas aeruginosa PAO1. J Photochem Photobiol B 2019; 201: 111667.
53. Omwenga EO, Hensel A, Shitandi A, Goycoolea FM. Chitosan nanoencapsulation of flavonoids enhances their quorum sensing and biofilm formation inhibitory activities against an E. coli Top 10 biosensor. Colloids Surf B Biointerfaces 2018; 164: 125-33.
54. Qin X, Engwer C, Desai S, Vila-Sanjurjo C, Goycoolea FM. An investigation of the interactions between an E. coli bacterial quorum sensing biosensor and chitosan-based nanocapsules. Colloids and Surfaces B: Biointerfaces 2017; 149: 358-68.
55. Subhaswaraj P, Barik S, Macha C, Chiranjeevi PV, Siddhardha B. Anti-quorum sensing and anti-biofilm efficacy of cinnamaldehyde encapsulated chitosan nanoparticles against Pseudomonas aeruginosa PAO1. Lwt 2018; 97: 752-9.
56. Castillo-Juárez I, Maeda T, Mandujano-Tinoco EA, Tomás M, Pérez-Eretza B, García-Contreras SJ, Wood TK, García-Contreras R. Role of quorum sensing in bacterial infections. World J Clin Cases 2015; 3(7): 575.
57. Zhao G, Usui ML, Lippman SI, James GA, Stewart PS, Fleckman P, Olerud JE. Biofilms and inflammation in chronic wounds. Adv Wound Care 2013; 2(7): 389-99.
58. Afrasiabi S, Partoazar A. Targeting bacterial biofilm-related genes with nanoparticle-based strategies. Front microbiol 2024; 15: 1387114.
59. Mihai MM, Dima MB, Dima B, Holban AM. Nanomaterials for wound healing and infection control. Materials 2019; 12(13): 2176.