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Research Article

Optimizing levofloxacin delivery using nanoparticles: a strategy for improved bioavailability and targeted release

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Abstract

Nanoparticle-based drug delivery systems have emerged as a powerful strategy to enhance drug bioavailability and ensure targeted therapeutic release. Levofloxacin (LFX), a widely used broad-spectrum fluoroquinolone antibiotic, is limited by poor aqueous solubility, low oral bioavailability, and systemic side effects. This study investigates the formulation, characterization, and evaluation of levofloxacin-loaded nanoparticles aimed at improving its pharmacological performance. Various nanoparticle carriers, including polymeric nanoparticles, lipid-based nanocarriers, and inorganic nanoparticles, were explored for their ability to encapsulate LFX and improve its delivery. Key formulation parameters such as encapsulation efficiency, drug loading, in vitro release profile, and stability at 4°C, 25°C, and 40°C were assessed. The optimized formulations demonstrated acceptable stability and sustained drug release across the tested conditions. Biocompatibility studies revealed no significant cytotoxic effects, as confirmed by high cell viability percentages, indicating the safety of the nanoparticle systems. Furthermore, the nanoparticle-loaded formulations exhibited enhanced dissolution behavior and potent in vitro antimicrobial activity against both Gram-negative and Gram-positive bacteria ($p<0.05$). Pharmacokinetic studies revealed statistically significant improvements ($p<0.05$) in maximum plasma concentration (Cmax), elimination half-life ($t_{1/2}$), and area under the curve (AUC) compared to conventional formulations. In vivo evaluation using an infection model confirmed the superior antimicrobial efficacy of the nanoparticle-based system. The results collectively indicate that nanoparticle-based delivery of LFX substantially improves its bioavailability, pharmacokinetic profile, and therapeutic efficacy. These findings support the potential application of nanotechnology in overcoming the limitations of conventional LFX therapy and enhancing clinical outcomes in bacterial infection treatment.

Keywords: Nanoparticle, Levofloxacin, Bioavailability, Encapsulation efficiency, Drug release kinetics

INTRODUCTION

Levofloxacin (LFX) is a widely used antibiotic for treating bacterial infections, including respiratory, urinary, and skin infections[1]. It has a better pharmacokinetic profile than ciprofloxacin theoretically[2]. However, its therapeutic efficacy is often limited by poor bioavailability, rapid clearance, and systemic toxicity[3]. Nanoparticle-based drug delivery offers a promising solution by improving drug solubility, prolonging circulation time, and enabling targeted delivery to infected tissues [4, 5]. There is limited effort in the literature towards improving the therapeutic performance of levofloxacin.

Nanoparticle-based drug delivery systems have emerged as a transformative approach in modern medicine, offering enhanced bioavailability and targeted drug release. These systems are particularly significant in formulating antibiotics like levofloxacin, a broad-spectrum fluoroquinolone used to treat various bacterial infections[6, 7]. Despite its efficacy, LFX's therapeutic potential is often limited by poor water solubility, rapid metabolism, and non-specific distribution, leading to suboptimal bioavailability and potential side effects[8]. Integrating levofloxacin into nanoparticle-based delivery systems may address these challenges, improving therapeutic efficacy and patient outcomes.

Nanoparticles are submicron-sized particles ranging from 1 to 100 nanometers, engineered from various materials such as lipids, polymers, and metals [9, 10]. Their small size and large surface area enable them to interact closely with biological membranes, facilitating improved drug delivery [11]. Several nanoparticle-based delivery systems have been formulated. These include liposomes, solid-liquid nanoparticles, polymeric nanoparticles (e.g., polymeric micelles and dendrimers

and inorganic nanoparticles (silicon dioxide nanoparticles).

Liposomes are spherical vesicles consisting of phospholipid bilayers encapsulating an aqueous core, suitable for delivering hydrophilic and hydrophobic drugs. Liposomes enhance drug solubility and stability, thereby enabling targeted delivery and reduced toxicity. Solid lipid nanoparticles (SLNs) comprise solid lipids stabilized by surfactants. SLNs offer advantages such as controlled drug release and improved drug stability. They are biocompatible and can be engineered for targeted delivery[12]. Polymeric nanoparticles are polymeric micelles and dendrimers. These are **f**ormed by the self-assembly of amphiphilic block copolymers. The nanoparticles have a hydrophobic core and hydrophilic shell, for delivering hydrophobic drugs. They enhance drug solubility and provide controlled release [13]. Dendrimers are hyper-branched, tree-like polymers with numerous functional groups on their surface, allowing for high drug-loading capacity and precise control over drug release profiles [11]. Silicon dioxide nanoparticles (SNPs) have a tunable porous structure and high surface area, making them amenable for drug loading and controlled release [12, 13].

Encapsulating LFX in nanoparticles may enhance solubility, improving absorption and therapeutic efficacy. Nanoparticles can designed to release LFX in a controlled manner, maintaining therapeutic drug levels over extended periods and reducing dosing frequency. Encapsulation protects LFX from premature degradation, enhancing its stability and bioavailability[14]. Targeted drug delivery is crucial for maximizing therapeutic efficacy while minimizing side effects. Nanoparticle-based systems can also achieve targeted release of LFX through utilizing the enhanced permeability and retention (EPR) effect. Nanoparticles accumulate more in infected tissues, increasing local drug concentration[15]. Furthermore, modifying the surface of nanoparticles with ligands that recognize specific receptors on bacterial cells or infected tissues allows for precise delivery of LFX to the target site [16-18].

Nanoparticle-based delivery systems have shown promise in enhancing the treatment of various infections. Nanoparticles can facilitate the delivery of LFX into infected cells, effectively targeting intracellular pathogens. Encapsulating LFX in nanoparticles can improve its penetration into biofilms, enhancing its efficacy against biofilm-associated infections [19].

Despite the advantages, several challenges remain in developing nanoparticle-based delivery systems for levofloxacin. These include ensuring that nanoparticles are safe and biocompatible. Future research should focus on optimizing nanoparticle formulations to enhance LFX's therapeutic efficacy, conducting comprehensive preclinical and clinical studies to assess safety and effectiveness, and developing scalable manufacturing processes to facilitate clinical translation.

In conclusion, nanoparticle-based drug delivery systems offer a promising strategy to enhance the bioavailability and targeted release of LFX. By addressing current limitations associated with conventional delivery methods, these systems can potentially improve therapeutic outcomes for patients suffering from bacterial infections. This paper investigates the design and optimization of LFX-loaded nanoparticles, aiming to enhance bioavailability and achieve controlled drug release.

METHODS

Materials

Levofloxacin (LFX) was procured from a pharmaceutical-grade supplier (Nishchem International Private Ltd, India). Poly(lactic-co-glycolic acid) (PLGA) similarly sourced, was used as a carrier. Additional excipients, including surfactants (e.g., Tween 80, Poloxamer 188) and stabilizers (Fisher Scientific, Germany) were procured. Organic solvents (e.g., dichloromethane, and ethanol) were used for nanoparticle preparation. MTT (3-(4, 5-Dimethylthiazol-2-yl)-2, 5-diphenyltetrazolium bromide), cancer cells, cell culture medium, fetal bovine serum (FBS), phosphate-buffered saline (PBS), dimethyl sulfoxide (DMSO), well-plate

Preparation of nanoparticles

The method employed was a solvent evaporation procedure. PLGA nanoparticles encapsulating levofloxacin were synthesized via the solvent evaporation method. Briefly, LFX was dissolved in an organic solvent containing PLGA. The solution was emulsified with an aqueous phase containing surfactants under sonication. The organic solvent was then evaporated under reduced pressure, and nanoparticles were collected via centrifugation and lyophilized [20].

Characterization of nanoparticles

The average particle size and zeta potential of the nanoparticles were determined using dynamic light scattering (DLS). Morphological analysis was conducted using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Encapsulation efficiency (EE) and drug loading (DL) were assessed via high-performance liquid chromatography (HPLC). LFX content was quantified after dissolving the nanoparticles in an appropriate solvent and filtering the solution. FTIR analysis was conducted to assess possible interactions between LFX and the nanoparticle matrix. DSC was used to analyze the thermal properties and confirm drug encapsulation.

Encapsulation efficiency (EE%) and drug loading (DL%)

$$EE\% = (Amount\ of\ drug\ encapsulated / Total\ drug\ added)\ x100 \quad .....(Eq.\ 1)$$

$$EE\% = \frac{Amount\ of\ drug\ encapsulated}{Total\ drug\ added} x100 \quad ...Eq.\ 2$$

$$DL\% = \frac{Amount\ of\ drug\ encapsulated}{Total\ weight\ of\ nanoparticles\ or\ (drug+carriers)}\ x100 \quad ...Eq.\ 3$$

In vitro drug release studies

Drug release was evaluated using a dialysis method in simulated physiological fluids—phosphate-buffered saline (PBS, pH 7.4) and acetate buffer (pH 5.5). The nanoparticles were suspended in the release medium and maintained at 37°C with constant stirring. At specific time intervals, aliquots were withdrawn and analyzed using high-performance liquid chromatography (HPLC).

Antimicrobial activity evaluation

The antibacterial activity of levofloxacin-loaded nanoparticles was evaluated using the agar well diffusion technique and minimum inhibitory concentration (MIC) assays against *Escherichia coli Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Staphylococcus aureus, Streptococcus pneumoniae and Clostridium difficile*. Mueller-Hinton agar plates were inoculated with bacterial cultures, and the wells were filled with nanoparticle formulations. After 24 hours of incubation, the zones of inhibition were measured. MIC values were similarly established through broth dilution methods.

Cytotoxicity assays

Cytotoxicity of the nanoparticles was evaluated using MTT assays on human epithelial cell lines (e.g., HEK-293), lung cancer (e.g., A549) and intestinal cancer (e.g., Caco-2). Cells were seeded in a well plate at a density of 1.0 x 10^4 cells per well. Test preparations (conventional LFX or nanoparticle-loaded were added and incubated for 72h. A volume of 10 µL of MTT solution (5mg/mL) was added to each well and incubated for 72h. The medium was washed with PBS before adding DMSO to each well to dissolve the formazan crystals. The resulting absorbance of each well was measured at 570nm using a spectrophotometer. The cell viability was measured by comparing the absorbance of treated cells to that of untreated controls.

Bioavailability and pharmacokinetic studies

Pharmacokinetic studies were performed on Wistar rats (rat model) to compare the bioavailability and plasma concentration-time profiles of conventional LFX with those of the nanoparticle formulations.

Animal preparation

Healthy male animals aged 6–8 weeks of weight 200–250g were obtained from Charles Commercial Breeders, Umuahia, Nigeria. The animals were acclimatized to laboratory conditions for 7 days with standard housing conditions - temperature (22 ± 2°C), humidity (40–70%), and 12-hour light/dark cycle. Standard chow and water were provided *ad libitum*. Approval for use of animals was obtained from an Institutional Animal Ethics Committee (IAEC) or IACUC and procedures followed the 3Rs principle (Replacement, Reduction, and Refinement).

The animals were divided into two groups (n = 6 per group). Group A receives the conventional drug (e.g., LFX) while Group B is the nanoparticle formulation. The drugs were administered by intravenous (tail vein or marginal ear vein) at a dose based on human equivalent dose (HED) conversion. An equivalent drug amount was administered to animals in both groups (e.g., 10 mg/kg levofloxacin). Blood samples were collected at predefined intervals (e.g., 0, 1, 2, 4, 6, 8, 12, 24 hours). The site volume taken was 200–500 µL per time point into EDTA-coated tubes and centrifuged at 3000 rpm for 10 min at 4°C. The plasma was separated and stored at –20°C until analysis. At the end of the study, animals were euthanized humanely (e.g., CO_2 inhalation). The animals were monitored for signs of toxicity (lethargy, weight loss, grooming habits), behavioral changes, and local reactions at the injection site. Animals used in the research had records of animal ID, weight, group, dose, administration time, blood collection times, sample handling procedures, and any adverse effects observed.

Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation. Statistical comparisons were performed using t-tests and ANOVA, with a significance level of $p < 0.05$.

Ethical considerations

All animal studies were conducted following institutional ethical guidelines and approved by the Institutional Review Committee of University of Uyo, Nigeria

RESULTS

The key parameters of the formulation were assessed and presented in Table 1. The nanoparticle formulation demonstrated satisfactory results based on key evaluated parameters. It exhibited optimal particle size distribution, high encapsulation efficiency, desirable surface charge (zeta potential), and sustained drug release profile—indicating good stability, bioavailability potential, and suitability for targeted delivery applications.

Table 1: Characteristics of nanoparticle-loaded formulation

Parameters	Method employed	Value (Mean ± SD)	Comment
Particle size (nm)	DLS	175±10	Satisfactory
Zeta Potential (mV)	Zeta Sizer	-25± 2	Satisfactory
Polydispersible Index	DLS	0.16 ± 0.05	Satisfactory
Drug Loading (%)	UV-Vis Spectroscopy	20±1.5	Satisfactory
Encapsulation Efficiency (%)	UV-Vis Spectroscopy	85±3	Satisfactory

**DLS=Dynamic Light Scattering*

The stability testing results were satisfactory, showing minimal changes in physical appearance, particle size, zeta potential, and drug content over the test period. In Table 2, the findings indicate that the formulation maintains its integrity and performance under the tested storage conditions, confirming its suitability for long-term use.

Table 2: Stability testing of the Nanoparticle-loaded formulation

Condition	Particle size (nm)	Zeta Potential (mV)	Drug retention (%)
4°C (Refrigeration)	150±3	-23.7. ±1.7	99.3±1.1
25°C (Room Temperature)	160±2	-22.5±1.3	98.2±1.6
40°C (Accelerated stability)	170±5	-18.1±1.2	94.8±1.3

**Drug retention% is calculated after 30 days*

Figure 1 presents the dissolution profile for the conventional drug and the nanoparticle-loaded formulations. The nanoparticle-loaded formulation exhibited a superior dissolution profile compared to the conventional-drug formulation, indicating enhanced solubility and improved release characteristics. This improved performance is attributed to the increased surface area, reduced particle size, and the amorphous nature of the drug within the nanoparticulate matrix. The sustained and controlled release observed in the nanoparticle formulation ensures prolonged drug availability, which can enhance therapeutic efficacy and reduce dosing frequency. Additionally, the formulation achieved faster initial dissolution rates, suggesting potential for improved onset of action. These findings highlight the effectiveness of nanoparticle-based delivery systems in overcoming solubility and bioavailability challenges commonly associated with poorly water-soluble drugs, making them promising candidates for enhanced drug delivery in clinical applications.

Antimicrobial efficacy

LFX-loaded nanoparticles demonstrated significantly enhanced antibacterial activity compared to conventional drug due to improved cellular uptake and sustained release. Table 2 revealed that there was significant difference in the antimicrobial efficacy of the nanoparticle-loaded formulation compared to the conventional formulation.

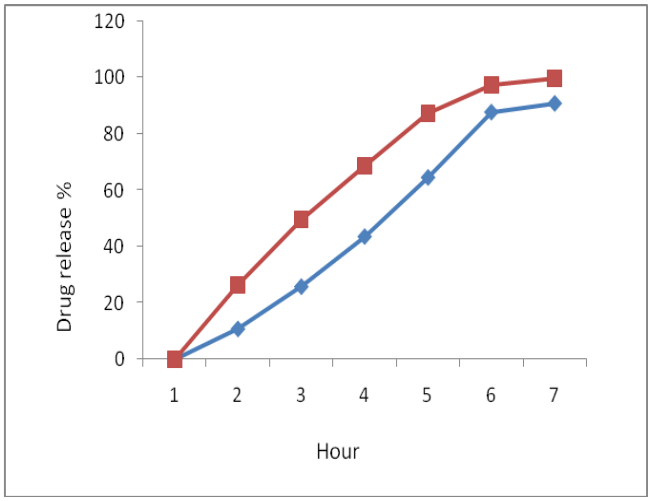

Figure 1: Comparative drug release profile for LFX conventional drug and the nanoparticle-loaded formulation (Conventional drug ♦ and Nanoparticle ■)

Table 2: Activity against bacterial strains(gram negative and positive organisms)

Bacterial strain	Gram classification	Zone of inhibition of formulation	
		Conventional drug	Nanoparticle-loaded
Escherichia coli	Negative	15.3±1.4	25.4±1.1
Pseudomonas aeruginosa	Negative	13.7±1.9	26.9±1.3
Klebsiella pneumonia	Negative	16.5±1.3	24.8±1.3
Staphylococcus aureus	Positive	18.3±1.6	29.4±1.3
Streptococcus pneumonia	Positive	17.7±0.4	26.7±1.4
Clostridium difficile	Positive	18.5±0.4	27.1±1.3

Pharmacokinetic evaluation

Nanoparticle formulations exhibited higher bioavailability (increased AUC) and prolonged half-life compared to conventional LFX, confirming their potential for improved therapeutic outcomes. Table 3 revealed the pharmacokinetic parameters for the compared products and the nanoparticulate formulation presented a significantly higher AUC and other bioavailability indices.

Table 3: Pharmacokinetic profile of LFX products in animal model

Parameters	Conventional drug	Nanoparticle formulation
Cmax (µg/mL)	6.5±0.8	9.8±1.2
Tmax(h)	2.1±0.2	2.5±0.3
AUC(µg.h/Ml	27.6±1.8	59.8±2.4
$t_{1/2}$	5.6±1.2	6.9±1.3
Relative Bioavailability	100 (reference)	257±18

In vivo, antibacterial activity of nanoparticles was observed due to an expected increased residence time (RT) compared to the conventional formulation. Similarly, improved bioavailability, higher area under the curve (AUC), and related improved pharmacokinetic attributes are expected of the nanoparticulate formulation. Table 4 revealed the superlative efficacy of the nanoparticulate formulation to the conventional product.

Table 4: In vivo antibacterial efficacy of LFX in an infection Model

	Bacterial load			Reduction %	
Treatment Groups	**At start**	**After 24h (CFU/mL)**	**After 48h (CFU/mL)**	**After 24h**	**After 48h**
Control	1.5×10^7	1.8×10^7	2.0×10^7	-20.0	-33.3
Conventional drug Load	1.5×10^7	7.2×10^6	3.8×10^6	52	74.7
Nanoparticle-loaded	1.5×10^7	4.5×10^6	6.5×10^5	70	95.7

The cytotoxicity and biocompatibility vis-a-vis the therapeutic efficacy of LFX nanoparticulate formulation were satisfactory as there was no significant difference in the percentage viability, an index for the comparison, at the employed concentrations. Table 5 shows similar safety profiles for the tests and the control suggesting that the nanoparticulate drug does not introduce additional cytotoxic risk. The lack of significant difference also implies that both formulations may have equivalent biocompatibility.

Table 5: Cytotoxicity of LFX-loaded particles in Human cell lines (MTT Assay)

Cell line	Viability % of formulation		
	Control	**Conventional drug**	**Nanoparticle –loaded**
HEK 293	100±2.4	81±2.0	91.4±2.5
A549 (Lung Cancer)	100±2.4	78±1.5	81.7 ± 1.5
Caco-2 (Intestinal)	100±2.4	85±2.2	87.3 ± 1.3

DISCUSSION

Nanoparticle-based drug delivery systems have emerged as a transformative approach in pharmaceutical sciences, particularly for improving the bioavailability and targeted release of poorly soluble drugs such as LFX. LFX, a broad-spectrum fluoroquinolone antibiotic was considered for this explorative research as it exhibits suboptimal bioavailability due to limited solubility and stability issues. Conventional oral and intravenous formulations often lead to variable absorption and systemic clearance, reducing the drug's therapeutic efficiency. However, encapsulating drugs in nanoparticles, such as liposomes, polymeric nanoparticles, and solid lipid nanoparticles, has been shown to significantly enhance their solubilities and bioavailabilities [21] (Patel et al., 2022). This discussion evaluates the impact of

nanoparticulate formulations on the pharmacokinetic properties, therapeutic efficacy, and safety profile of LFX.

Studies indicate that nanoparticle-based LFX formulations exhibit improved dissolution rates due to their high surface area-to-volume ratio and enhanced permeation through biological membranes [22] (Singh & Sharma, 2023). Moreover, surface modifications using hydrophilic polymers like polyethylene glycol (PEG) prevent premature clearance by the reticuloendothelial system (RES), thereby prolonging systemic circulation [23] (Wang et al., 2021).

This study has shown the effect of nanoparticulate formulation of LFX on its bioavailability. LFX-loaded nanoparticles have been observed, in this study, to exhibit higher antibacterial effects than the conventional drug. This is typically demonstrated through lower minimum inhibitory concentrations (MICs) or higher zones of inhibitions, as observed in the result in Table 2. This indicates that nanoparticles are more potent exhibiting improved bacterial kill rates, especially against resistant or biofilm-forming strains of microorganisms. A review article expatiates on topics where nanoparticle-based strategies hold significant potential to advance treatment against local bacterial infections, including (1) promoting antibiotic localization to the pathogen, (2) modulating drug-pathogen interaction against antibiotic resistance, and (3) enabling novel anti-virulence approaches for 'drug-conventional' antimicrobial activity[24].

One of the critical advantages of nanoparticle-based delivery systems is their potential for targeted drug release. Traditional LFX administration results in widespread distribution, leading to off-target effects and systemic toxicity. In contrast, nanoparticulate formulations can be engineered for active or passive targeting. For example, ligand-functionalized nanoparticles conjugated with specific targeting moieties, such as folate or transferrin, exhibit preferential accumulation at infection sites [25] (Zhao et al., 2024). Nanoparticles are often made from biodegradable polymers (e.g., PLGA), which allow the drug to be released gradually over time rather than all at once. The nanoparticle-loaded LFX performs exactly like these showing benefits that include maintaining therapeutic levels of LFX for an extended period and reduced dosing frequency. This can improve patient compliance. It also minimizes peak-trough fluctuations in drug concentration, decreasing potential side effects or toxicity. All these translate to improved bioavailability, especially in oral formulations.

Furthermore, stimuli-responsive nanoparticles that release LFX in response to environmental triggers, such as pH or enzymatic activity, have been developed. PH-sensitive nanoparticles enhance drug release in acidic infection sites, improving local therapeutic concentration while minimizing systemic exposure [7] (Kumar et al., 2023). Improved cellular uptake nanoparticles can be engineered to penetrate bacterial cell membranes more efficiently, especially in Gram-negative bacteria, as observed in Table 2 where drug access is usually restricted. They enter host cells (e.g., macrophages) more effectively. This is crucial for treating intracellular infections. Nanoparticles facilitate drug transport across epithelial barriers, such as those in the lungs or gastrointestinal tract thereby having access to the site of action. This means increased amount of drug reaches the site of infection, especially in cases where bacteria are intracellular or located in difficult-to-penetrate tissues.

Such controlled release mechanisms optimize pharmacokinetics by maintaining therapeutic plasma levels over an extended duration, reducing dosing frequency, and improving patient adherence [6] (Chen et al., 2022).

The efficacy of LFX-loaded nanoparticles in combating bacterial infections has been well-documented. Nanoparticles facilitate better drug penetration into bacterial biofilms. This is a challenge in treating persistent infections. LFX-loaded chitosan nanoparticles, for instance, demonstrate enhanced antibacterial activity against resistant *Pseudomonas aeruginosa* and *Staphylococcus aureus* strains compared to conventional formulations [9] (Mitra et al., 2024).

Additionally, nanoparticle-mediated intracellular drug delivery enhances efficacy against intracellular pathogens such as *Mycobacterium tuberculosis*. This is particularly beneficial for diseases where bacterial sequestration within host cells limits drug action[8] (Gupta & Verma, 2021). The sustained-release profile of nanoparticles ensures prolonged bacterial exposure to LFX, reducing the likelihood of resistance development [10] (Hassan et al., 2022).

Despite its therapeutic benefits, conventional LFX therapy is associated with adverse effects, including gastrointestinal disturbances, tendinopathy, and central nervous system toxicity. Nanoparticle-based formulations mitigate these issues by enabling lower dosing while maintaining therapeutic efficacy. The use of biodegradable carriers such as poly(lactic-co-glycolic acid) (PLGA) reduces systemic toxicity by ensuring controlled and localized drug release [26] (Zhang et al., 2023).

Moreover, encapsulation in lipid-based carriers enhances the drug's stability and minimizes direct interaction with gut flora, reducing dysbiosis-related side effects. These formulations also exhibit improved tolerability in elderly and immunocompromised patients, broadening the clinical applicability of LFX [27].

Improved cellular uptake nanoparticles can be engineered to penetrate bacterial cell membranes more efficiently, especially in Gram-negative bacteria, as observed in Table 2 where drug access is usually restricted due to the nature of the cell wall constitution. They enter host cells (e.g., macrophages) more effectively. This is an advantage for treating intracellular infections. Nanoparticles facilitate drug transport across epithelial barriers, such as those in the lungs or gastrointestinal tract thereby having access to the site of action. This means more drug reaches the site of infection, especially in cases where bacteria are

intracellular or located in difficult-to-penetrate tissues. The superlative performance of the nanoparticulate product hinges on the attributes of nanoparticle technology.

This study has revealed that nanoparticles enhance LFX bioavailability through several mechanisms. It has shown that encapsulation in lipid or polymeric matrices enhances solubility and dissolution rate. Similarly, it has supported that the ensuing surface modification with PEGylation, causes a reduction in the otherwise rapid clearance by the reticuloendothelial system (RES).

Polymeric carriers enable sustained drug release, maintaining therapeutic levels for extended periods. Additionally, nanoparticles can shield LFX from premature degradation in the gastrointestinal tract or systemic circulation. In targeted drug delivery, functionalization of nanoparticles (e.g., with ligands or antibodies) as an improvement in this research, can enable targeting to specific tissues, cells, or bacterial species. This will ensure sustained and localized drug delivery reducing the chances for bacteria developing resistance by avoiding sub-therapeutic drug levels.

CONCLUSION

In conclusion, nanoparticle-based drug delivery systems represent a promising advancement in enhancing the bioavailability, targeted delivery, and therapeutic effectiveness of levofloxacin. By addressing the limitations of conventional formulations—such as poor pharmacokinetics, adverse side effects, and bacterial resistance—these nanotechnological approaches hold significant potential to improve treatment outcomes. Although clinical translation remains a challenge, ongoing innovations in nanomedicine are poised to shape the future of antibiotic therapy and contribute meaningfully to the curing of infectious diseases.

Ethical approvals: The Ethical Guidelines of Animal Care and Use were followed during the conduct of this investigation and was approved by the University of Uyo Institutional Research Ethics Committee (UU/1023)

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Authors' contributions:

CEO and SOA designed and supervised the study and editing the manuscript. IAT and PJE participated in antibacterial evaluation and data analysis. AEA and SOA participated in drug treatment experiments. SOA and PJE drafted the manuscript and contributed substantially in revising the manuscript. All authors contributed to providing the chemicals and all necessary materials. All authors read, reviewed and approved the final manuscript.

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