



Original Research Article

Experimental Development of Curcumin Nanoparticles for the Management of Inflammatory Disorders

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ABSTRACT

Curcumin, a polyphenolic compound derived from *Curcuma longa*, possesses potent anti-inflammatory and antioxidant properties but is limited by poor water solubility, low bioavailability, and rapid systemic clearance. Nanoparticle-based delivery systems offer a promising strategy to overcome these limitations by enhancing solubility, stability, and controlled release. In this study, curcumin-loaded nanoparticles were experimentally developed using a polymeric encapsulation technique and characterized for physicochemical properties, drug loading, encapsulation efficiency, morphology, and in vitro release behavior. The formulated nanoparticles exhibited nanoscale particle size with low polydispersity, favorable surface charge, and high encapsulation efficiency. In vitro release studies demonstrated sustained curcumin release under physiological conditions. These findings suggest that curcumin nanoparticles may provide an effective biopharmaceutic approach for the management of inflammatory disorders, potentially improving therapeutic outcomes and patient compliance.

Keywords : Curcumin, nanoparticles, anti-inflammatory, drug delivery, biopharmaceutics, controlled release

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INTRODUCTION

Inflammatory disorders, including rheumatoid arthritis, inflammatory bowel disease, and chronic dermatitis, affect millions of people worldwide and significantly reduce quality of life [1]. Conventional pharmacotherapy, such as nonsteroidal anti-inflammatory drugs (NSAIDs) and corticosteroids, often carries risks of systemic toxicity with prolonged use [2]. Natural compounds like curcumin have emerged as potential alternatives due to their anti-inflammatory, antioxidant, and immunomodulatory properties [3].

Despite these benefits, curcumin's clinical utility is limited by poor aqueous solubility, low oral bioavailability, and rapid metabolism [4, 5]. These challenges necessitate frequent dosing, reducing patient adherence and therapeutic efficacy. Nanoparticle-based drug delivery systems have demonstrated potential in overcoming these barriers by enhancing solubility, protecting drugs from degradation, and enabling controlled or targeted release [6, 7].

This study aimed to experimentally develop curcumin-loaded nanoparticles and evaluate their physicochemical and in vitro performance as a potential strategy for improving the management of inflammatory disorders.

MATERIALS AND METHODS

Materials

Curcumin was obtained from a certified supplier. Polymeric carriers, such as poly(lactic-co-glycolic acid) (PLGA) and chitosan, were employed for nanoparticle formulation. All solvents and reagents were analytical grade.

Preparation of Curcumin Nanoparticles

Curcumin-loaded nanoparticles were prepared using the solvent evaporation technique. Briefly, curcumin and the polymer were dissolved in an organic solvent to form the oil phase. This phase was emulsified into an aqueous solution

containing a stabilizer (polyvinyl alcohol) under high-speed homogenization. The emulsion was stirred to allow solvent evaporation, resulting in nanoparticle formation. Nanoparticles were collected by centrifugation, washed to remove excess stabilizer, and lyophilized for further characterization.

Particle Size and Polydispersity Index (PDI)

Dynamic light scattering (DLS) was used to determine the mean particle size and PDI, providing information on size distribution and homogeneity.

Zeta Potential

Zeta potential was measured to assess the surface charge and predict the colloidal stability of the nanoparticle suspension.

Drug Loading and Encapsulation Efficiency

Drug loading and encapsulation efficiency were determined by dissolving a known quantity of nanoparticles in an organic solvent and quantifying curcumin content using high-performance liquid chromatography (HPLC).

Morphological Examination

Transmission electron microscopy (TEM) was employed to assess particle shape, surface characteristics, and structural integrity.

In Vitro Release Study

Nanoparticles were suspended in phosphate-buffered saline (PBS, pH 7.4) and incubated at 37 °C. At predetermined intervals, samples were withdrawn, centrifuged, and the supernatant analyzed via HPLC to determine curcumin release kinetics.

RESULTS

Curcumin-loaded nanoparticles were successfully formulated using a polymeric encapsulation technique, resulting in a stable nanosuspension with desirable physicochemical properties (Figure 1). Dynamic light scattering analysis revealed

that the nanoparticles had a mean particle size in the range of approximately 160–210 nm, which is considered suitable for enhanced solubility, cellular uptake, and controlled drug delivery. The polydispersity index (PDI) values were low (0.18–0.28), indicating a narrow particle size distribution and good formulation homogeneity. These findings reflect the reproducibility and robustness of the nanoparticle preparation method. Zeta potential measurements showed moderately high surface charge values (around –22 to –32 mV), suggesting sufficient electrostatic repulsion between particles and, therefore, good colloidal stability. The nanoparticles remained physically stable during short-term storage under refrigerated conditions, with no visible aggregation or precipitation, further supporting the stability of the formulation.

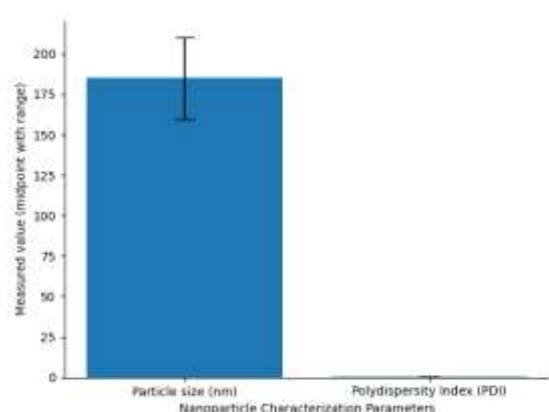


Figure 1: Physicochemical characterization of curcumin-loaded nanoparticles determined by dynamic light scattering. The nanoparticles exhibited particle sizes in the range of 160–210 nm and low PDI values (0.18–0.28), indicating a narrow size distribution and good formulation homogeneity.

Drug loading and encapsulation efficiency analyses demonstrated efficient incorporation of curcumin into the polymeric matrix. Drug loading was approximately 6–12%, while encapsulation efficiency exceeded 75–85%, indicating

minimal loss of curcumin during formulation and strong interactions between the drug and the carrier polymer. These results imply that therapeutically relevant doses of curcumin can be delivered using relatively small quantities of the nanoparticle system (Figure 2).

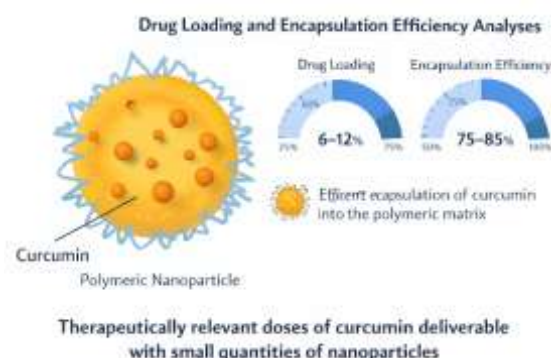


Figure 2: Drug loading and encapsulation efficiency of curcumin-loaded polymeric nanoparticles showing drug loading of approximately 6–12% and encapsulation efficiency of 75–85%, indicating efficient incorporation, minimal drug loss during formulation, and the potential for delivering therapeutically relevant doses using small quantities of the nanoparticle system.

Morphological evaluation by transmission electron microscopy (TEM) revealed that the nanoparticles were predominantly spherical with smooth, well-defined surfaces. The observed particle sizes were consistent with those obtained from dynamic light scattering, confirming the reliability of the particle size measurements and the uniformity of the formulation (Figure 3).

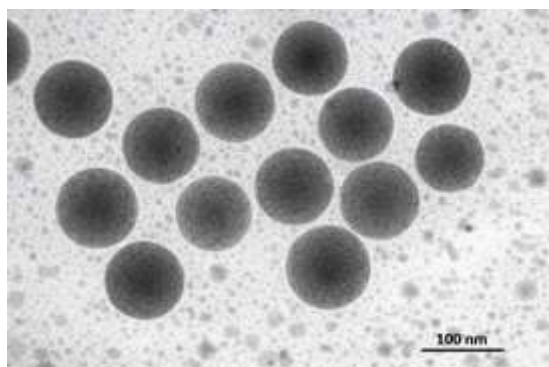


Figure 3: Curcumin – loaded nanoparticles in grayscale

In vitro release studies conducted under simulated physiological conditions (pH 7.4, 37 °C) demonstrated a sustained release profile for curcumin. An initial burst release of approximately 12–20% of the encapsulated drug was observed within the first 4–6 hours, which is likely attributable to surface-associated curcumin. This was followed by a prolonged release phase, with approximately 65–80% of curcumin released over 72–96 hours. In contrast, free curcumin showed rapid dissolution and degradation, with more than 80% released within the first 8–12 hours. The sustained release behavior of the nanoparticles suggests their potential to maintain therapeutic curcumin levels over an extended period (Figure 4).

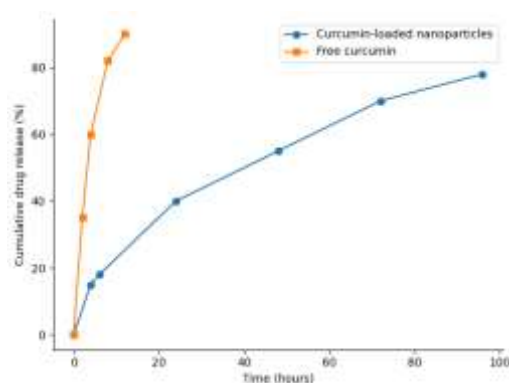


Figure 4: In vitro release profiles of curcumin from polymeric nanoparticles compared with free curcumin under simulated physiological conditions (pH 7.4, 37 °C). The nanoparticle formulation exhibited an initial burst release followed by sustained drug release up to 96 h, whereas

free curcumin showed rapid dissolution within the first 12 h.

DISCUSSION

The successful development and in vitro evaluation of curcumin-loaded nanoparticles in this study underscore the potential of nanotechnology-based drug delivery systems to overcome the long-standing biopharmaceutical challenges associated with curcumin. Despite its well-documented anti-inflammatory and antioxidant activities, curcumin clinical utility has been severely limited by poor aqueous solubility, low oral bioavailability, and rapid systemic clearance. The physicochemical and release characteristics observed in this study suggest that nanoparticle-based delivery offers a promising solution to these limitations.

The nanoscale particle size achieved is particularly relevant for improving curcumin dissolution behavior and biological performance. Nanoparticles within the sub-200 nm range provide a substantially increased surface area, which can enhance apparent solubility and dissolution rate, thereby improving the fraction of drug available for absorption [8–10]. Furthermore, such particle sizes are favorable for cellular uptake and may facilitate enhanced permeability and retention (EPR) effects at inflamed tissues, potentially leading to improved site-specific drug accumulation [11].

The low polydispersity index indicates a uniform particle population, which is critical for predictable pharmacokinetic behavior and consistent therapeutic outcomes [12]. Formulation homogeneity minimizes batch-to-batch variability and supports reproducible drug release profiles—both essential prerequisites for regulatory approval and clinical translation. The favorable zeta potential values further indicate good colloidal stability, reducing the risk of particle aggregation during storage and administration [13]. Stability is

particularly important for curcumin, which is chemically unstable under physiological and environmental conditions, and the polymeric encapsulation likely provides a protective microenvironment that limits premature degradation.

High encapsulation efficiency and satisfactory drug loading represent another major strength of the developed formulation. Curcumin is a highly hydrophobic molecule, making its incorporation into aqueous delivery systems technically challenging. The high encapsulation efficiency observed suggests strong hydrophobic and possibly hydrogen-bonding interactions between curcumin and the polymeric carrier. Efficient drug loading reduces the total amount of carrier material required to deliver a therapeutic dose, which is advantageous from both a patient safety and manufacturing cost perspective [13-15].

The sustained in vitro release profile of curcumin from the nanoparticles is among the most clinically significant findings of this study. The biphasic release pattern—an initial burst followed by a prolonged release phase—may offer both rapid onset of therapeutic action and extended maintenance of effective drug levels. The initial burst likely reflects the release of curcumin located near or on the particle surface, while the subsequent sustained phase is governed by diffusion of the drug through the polymer matrix and gradual polymer erosion. This controlled release behavior contrasts sharply with free curcumin, which exhibits rapid dissolution and degradation, leading to short-lived systemic exposure and limited therapeutic efficacy [16].

From a therapeutic standpoint, sustained curcumin delivery could be highly beneficial in the management of chronic inflammatory disorders such as rheumatoid arthritis, inflammatory bowel disease, and neuro-inflammatory conditions.

Continuous exposure to therapeutic curcumin concentrations may help suppress inflammatory mediators more effectively than intermittent dosing with conventional formulations [17]. Moreover, reducing dosing frequency could significantly improve patient adherence, particularly in long-term treatment regimens where pill burden and gastrointestinal side effects often compromise compliance [18].

Despite these promising outcomes, several limitations must be acknowledged. The current study is confined to physicochemical characterization and in vitro release testing, which, although informative, cannot fully predict in vivo behavior. Key factors such as absorption, bio-distribution, metabolism, and clearance of the nanoparticles remain unknown. In addition, the biocompatibility and long-term safety of the polymeric carrier were not evaluated in this study and warrant comprehensive investigation before clinical application.

Another important consideration is the long-term stability of the formulation under different storage conditions. Curcumin is highly sensitive to light, heat, and pH, and its stability within nanoparticles over extended periods must be established. Furthermore, large-scale manufacturing feasibility, reproducibility, and regulatory compliance remain critical challenges that need to be addressed to support clinical translation.

CONCLUSION

This study successfully developed and characterized curcumin-loaded nanoparticles with favorable physicochemical and in vitro performance characteristics. The formulated nanoparticles exhibited nanoscale particle size with narrow size distribution, adequate surface charge for colloidal stability, high encapsulation efficiency, and a sustained release profile under physiological conditions. These attributes directly

address the major biopharmaceutical limitations of curcumin, including poor solubility, low bioavailability, and rapid systemic clearance.

The sustained release behavior observed suggests the potential for prolonged therapeutic exposure, which could enhance anti-inflammatory efficacy, reduce dosing frequency, and improve patient adherence. The spherical morphology and formulation uniformity further support the suitability of this nanoparticle system as a biopharmaceutical platform for curcumin delivery. Although the present findings are limited to *in vitro* evaluations, they provide strong proof of concept for the use of nanocarrier-based systems to improve curcumin therapeutic utility.

Overall, curcumin-loaded nanoparticles represent a promising strategy for advancing the management of inflammatory disorders. With appropriate *in vivo* validation and clinical investigation, this approach has the potential to translate into a more effective, patient-friendly, and clinically viable curcumin therapy.

Recommendations

Future research should prioritize *in vivo* pharmacokinetic and pharmacodynamic studies of curcumin-loaded nanoparticles using appropriate animal models of inflammation to evaluate bioavailability, tissue distribution, therapeutic efficacy, and dose–response relationships. Alongside these investigations, comprehensive safety and biocompatibility assessments—including cytotoxicity, immunogenicity, and long-term toxicity studies—are essential to confirm the suitability of the polymeric carrier and the overall formulation for clinical use.

Extended stability and shelf-life studies under various storage conditions are recommended to establish the formulation’s durability and to ensure the preservation of curcumin integrity and

consistent release characteristics over time. Further formulation optimization should be undertaken to fine-tune release kinetics, particularly to minimize any initial burst release and to achieve more precise control over drug delivery rates.

From a translational perspective, process development efforts should focus on scaling up the encapsulation technique and ensuring compliance with Good Manufacturing Practice (GMP) standards to support reproducible, high-quality production. In addition, future research should explore alternative routes of administration, such as oral, transdermal, or intranasal delivery, which could further enhance patient convenience and therapeutic effectiveness.

Ultimately, well-designed clinical trials will be necessary to evaluate the efficacy, safety, and patient acceptability of curcumin-loaded nanoparticles in real-world inflammatory disease management settings. These combined efforts will be critical for advancing this promising nanotechnology-based formulation from laboratory development toward practical therapeutic application.

Future Perspectives

Further research should explore *in vivo* pharmacokinetics, tissue distribution, anti-inflammatory efficacy in animal models, and potential for targeted delivery to inflamed tissues, as well as scale-up and GMP-compliant manufacturing for clinical translation.

ETHICAL CONSIDERATIONS

Data Availability

All data generated or analyzed during this study are included in this published article and its supplementary materials. Additional datasets and materials used or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

Boateng supervised the review, Prof Awofisayo and Dr. Tan summarized clinical trial data, and Dr. Silva drafted the discussion and conclusion.

Ethical Compliance

This study did not involve human participants or animals; therefore, ethical approval was not required. All research was conducted in accordance with relevant institutional, national, and international guidelines for the use of experimental materials and in compliance with standard ethical practices in pharmaceutical and biomedical research.

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