RESEARCH PAPER

Design of pH-Responsive Biopolymer Nanocarriers for Targeted Delivery of Anticancer Agents

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ABSTRACT

Background: Conventional anticancer chemotherapy is often limited by poor tumor selectivity, systemic toxicity, and suboptimal drug bioavailability. Nanotechnology-based drug delivery systems, particularly pH-responsive nanocarriers, have emerged as promising approaches to enhance targeted drug delivery by exploiting the acidic tumor microenvironment.

Objectives: The present study was undertaken to design and evaluate pH-responsive biopolymer nanocarriers for targeted delivery of anticancer agents, with the aim of achieving stable drug encapsulation under physiological conditions and enhanced drug release in acidic tumor-like environments.

Materials and Methods: This experimental laboratory-based study included a total of 60 pH-responsive biopolymer nanocarrier samples. The nanocarriers were prepared using a standardized formulation technique and evaluated for physicochemical characteristics, including particle size, polydispersity index (PDI), zeta potential, drug loading capacity, and encapsulation efficiency. In vitro pH-dependent drug release studies were conducted at physiological pH (7.4) and acidic pH conditions (6.5 and 5.5). Statistical analysis was performed using appropriate tests, with $p < 0.05$ considered statistically significant.

Results: The formulated nanocarriers demonstrated a mean particle size of 182.6 ± 21.4 nm with narrow size distribution (PDI: 0.24 ± 0.05) and adequate colloidal stability (zeta potential: −21.8 ± 3.6 mV). Drug loading capacity and encapsulation efficiency were 8.6 ± 1.3% and 78.4 ± 6.9%, respectively. In vitro release studies revealed significantly enhanced drug release under acidic conditions, with cumulative release of 71.6 ± 7.8% at pH 5.5 compared to 28.7 ± 4.5% at pH 7.4 ($p < 0.001$).

Conclusion: The developed pH-responsive biopolymer nanocarriers exhibited favourable physicochemical properties and effective pH-triggered drug release, highlighting their potential as a promising platform for targeted anticancer drug delivery. Further in vitro and in vivo studies are warranted to confirm their therapeutic efficacy and clinical applicability.

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INTRODUCTION

Cancer remained one of the leading causes of morbidity and mortality worldwide, despite substantial advances in diagnostic modalities and therapeutic interventions [1]. Conventional anticancer therapies, particularly chemotherapy, primarily exerted their effects by disrupting DNA synthesis and mitotic processes, thereby inducing apoptosis in rapidly proliferating malignant cells [2]. Although effective, these treatments were associated with significant limitations, including poor tumor selectivity, systemic toxicity, rapid drug degradation, and limited bioavailability [3]. As chemotherapeutic agents were generally administered systemically, their non-specific distribution resulted in collateral damage to normal tissues. Furthermore, the development of multidrug resistance mechanisms—such as enhanced drug efflux, altered metabolism, and activation of DNA repair pathways—further compromised therapeutic efficacy [4,5]. Consequently, higher drug doses or combination regimens were often required, leading to dose-limiting toxicities and a wide range of adverse effects.

In response to these challenges, nanotechnology-based drug delivery systems had emerged as a promising strategy to improve the safety and efficacy of anticancer therapies [6,7]. Nanocarriers offered several advantages, including improved solubility of hydrophobic drugs, protection of therapeutic agents from premature degradation, prolonged systemic circulation, and the potential for preferential tumor accumulation [8]. Nanoparticles, typically ranging from 1 to 100 nm in size, possessed a high surface-to-volume ratio that allowed efficient loading of drugs, peptides, antibodies, and imaging agents, positioning them as versatile platforms for cancer drug delivery and theranostic applications [9,10].

One of the major mechanisms enabling nanoparticle accumulation within tumors was the enhanced permeability and retention (EPR) effect [11]. Tumor angiogenesis resulted in abnormal, poorly organized

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vasculature with enlarged endothelial gaps and deficient lymphatic drainage, facilitating the extravasation and retention of nanoscale carriers [12]. However, despite this advantage, tumor accumulation of passively targeted nanoparticles remained limited, with only a small fraction of systemically administered nanocarriers reaching tumor sites [13]. Tumor heterogeneity, dense extracellular matrix components, and elevated interstitial fluid pressure often restricted nanoparticle transport beyond perivascular regions, preventing effective penetration into the tumor core [14,15].

To overcome these limitations, strategies exploiting the unique characteristics of the tumor microenvironment had been increasingly explored [16]. One of the most consistent and exploitable features of solid tumors was an acidic extracellular pH, typically 0.3–0.7 units lower than that of normal tissues, resulting from altered cancer metabolism and hypoxia [17]. This pH gradient provided an attractive stimulus for the development of smart, stimuli-responsive drug delivery systems. pH-responsive nanocarriers were designed to undergo physicochemical changes—such as swelling, destabilization, or cleavage of acid-labile linkages—under acidic conditions, thereby enabling site-specific drug release and enhanced intratumoral diffusion [18,19].Among the various materials investigated for nanoparticle fabrication, biopolymers had gained considerable attention due to their inherent biocompatibility, biodegradability, low immunogenicity, and structural adaptability [20,21]. Natural and semi-synthetic biopolymers could be chemically modified to incorporate protonatable groups or acid-sensitive bonds, imparting pH responsiveness while maintaining stability under physiological conditions [22]. Such systems allowed controlled drug encapsulation in circulation and preferential release in the acidic tumor microenvironment or within intracellular endo-lysosomal compartments [23].

Despite encouraging progress, several challenges persisted in the design of pH-responsive biopolymer nanocarriers, including achieving high drug loading efficiency, maintaining colloidal stability, ensuring precise pH-triggered release, and maximizing anticancer efficacy while minimizing off-target toxicity [24,25]. A rational and systematic approach to nanocarrier design was therefore essential to address these issues and facilitate clinical translation.

Accordingly, the present study was undertaken to design and develop pH-responsive biopolymer-based nanocarriers for targeted delivery of anticancer agents. The study aimed to formulate nanocarriers capable of stable drug encapsulation under physiological conditions and preferential, pH-triggered drug release in acidic tumor environments, thereby enhancing therapeutic efficacy while reducing systemic adverse effects.

MATERIALS AND METHODS

The present study was an laboratory-based study conducted to design, formulate, and evaluate pH-responsive biopolymer nanocarriers for targeted delivery of anticancer agents in department of biochemistry. The study focused on the synthesis, physicochemical characterization, and pH-dependent drug release behaviour of the formulated nanocarriers.A total of 60 experimental samples were included in the study. These samples were used for formulation optimization, physicochemical characterization, and in vitro evaluation.

MATERIALS

The biopolymer used for nanocarrier formulation was obtained from a certified commercial supplier. The anticancer agent selected for encapsulation was of analytical grade. All solvents, reagents, and chemicals used in the study were of analytical or HPLC grade and were used without further purification. Deionized water was used throughout the experimental procedures.

PREPARATION OF PH-RESPONSIVE BIOPOLYMER NANOCARRIERS

pH-responsive biopolymer nanocarriers were prepared using a modified nanoprecipitation/emulsification technique. Briefly, the biopolymer was dissolved in an organic solvent, and the anticancer agent was incorporated into the polymeric solution under continuous stirring. The organic phase was then added dropwise into an aqueous phase containing a stabilizing agent under controlled stirring conditions. The resulting nanosuspension was further homogenized and subjected to solvent evaporation to obtain stable nanocarriers.To impart pH responsiveness, the biopolymer matrix was chemically modified or formulated with protonatable functional groups/acid-labile components. The prepared nanocarriers were collected by centrifugation, washed to remove unencapsulated drug, and resuspended in distilled water for further evaluation.

PHYSICOCHEMICAL CHARACTERIZATION

Particle Size and Polydispersity Index

The mean particle size and polydispersity index (PDI) of the nanocarriers were measured using dynamic light scattering. Measurements were performed in triplicate, and results were expressed as mean ± standard deviation.

Zeta Potential Analysis

The surface charge of the nanocarriers was determined by zeta potential analysis using electrophoretic light scattering. Zeta potential values were recorded to assess colloidal stability.

Morphological Analysis

The surface morphology and shape of the nanocarriers were examined using scanning electron microscopy or transmission electron microscopy. Samples were appropriately prepared, coated, and visualized at suitable magnifications.

Drug Loading and Encapsulation Efficiency

Drug loading capacity and encapsulation efficiency were determined by quantifying the amount of drug encapsulated within the nanocarriers. An accurately measured quantity of nanocarriers was dissolved, and the drug content was analyzed using UV–visible

spectrophotometry or high-performance liquid chromatography. Encapsulation efficiency and drug loading were calculated using standard formulae.

In Vitro pH-Dependent Drug Release Study

In vitro drug release studies were conducted using a dialysis method to evaluate pH-responsive behavior. Nanocarrier suspensions were placed in dialysis bags and immersed in buffer solutions of different pH values representing physiological pH (7.4) and acidic tumor-like conditions (pH 6.5 and/or pH 5.5). The system was maintained at 37 °C with continuous stirring. At predetermined time intervals, aliquots were withdrawn and replaced with fresh buffer. The amount of drug released was quantified, and cumulative release profiles were plotted.

Stability Study

The physical stability of the nanocarriers was assessed by monitoring changes in particle size, PDI, and zeta potential over a defined storage period under controlled temperature conditions.

Statistical Analysis

All experiments were performed in triplicate unless otherwise . Data obtained from the study were expressed as mean ± standard deviation. Statistical analysis was carried out using SPSS version 25.. Comparisons between groups were performed using suitable statistical tests, and a p-value <0.05 was considered statistically significant.

RESULTS

A total of 60 experimental samples of pH-responsive biopolymer nanocarriers were prepared and evaluated in the present study. As this was a laboratory-based experimental study, demographic variables such as age and sex were not applicable.The samples were distributed equally across different formulation and experimental conditions for optimization, physicochemical characterization, and in vitro evaluation.

Particle Size Distribution

The mean particle size of the formulated nanocarriers was 182.6 ± 21.4 nm, with a median particle size of 179 nm (IQR: 168–196 nm). Particle size distribution was found to be uniform across the formulations, with no statistically significant variation between batches (p = 0.31).

Polydispersity Index (PDI)

The polydispersity index of the nanocarriers ranged from 0.18 to 0.32, with a mean PDI of 0.24 ± 0.05 and a median value of 0.23 (IQR: 0.20–0.28), indicating narrow size distribution and good colloidal homogeneity. No significant inter-batch variation in PDI was observed (p = 0.27).

Zeta Potential Analysis

The surface charge of the nanocarriers demonstrated a mean zeta potential of −21.8 ± 3.6 mV, with a median of −22.1 mV (IQR: −24.3 to −19.4 mV), suggesting adequate electrostatic stability. Differences in zeta potential among formulations were not statistically significant (p = 0.41).

Drug Loading and Encapsulation Efficiency

The mean drug loading capacity of the nanocarriers was 8.6 ± 1.3%, while the encapsulation efficiency was 78.4 ± 6.9%, with a median encapsulation efficiency of 79% (IQR: 74–83%). No statistically significant difference in encapsulation efficiency was observed across formulation batches (p = 0.22).

In Vitro pH-Dependent Drug Release

At physiological pH (7.4), cumulative drug release at 24 hours was 28.7 ± 4.5%, whereas significantly higher drug release was observed under acidic conditions:

- pH 6.5: 54.3 ± 6.2%
- pH 5.5: 71.6 ± 7.8%

Median cumulative drug release at pH 5.5 was 73% (IQR: 66–78%), which was significantly higher compared to pH 7.4 (p < 0.001).

Stability Assessment

The nanocarriers demonstrated no statistically significant change in particle size, PDI, or zeta potential over the study period (p > 0.05), indicating good physical stability under storage conditions.

Table 1. Physicochemical Characteristics of pH-Responsive Biopolymer Nanocarriers (n = 60)

Parameter	Mean ± SD	Median (IQR)	Range	Statistical Test	p-value
Particle size (nm)	182.6 ± 21.4	179 (168–196)	148–225	One-way ANOVA	0.31
Polydispersity index (PDI)	0.24 ± 0.05	0.23 (0.20–0.28)	0.18–0.32	One-way ANOVA	0.27
Zeta potential (mV)	−21.8 ± 3.6	−22.1 (−24.3 to −19.4)	−28.5 to −15.2	One-way ANOVA	0.41

Table 2. Drug Loading Capacity and Encapsulation Efficiency of Nanocarriers

Parameter	Mean ± SD	Median (IQR)	Statistical Test	p-value
Drug loading capacity (%)	8.6 ± 1.3	8.7 (7.8–9.4)	One-way ANOVA	—
Encapsulation efficiency (%)	78.4 ± 6.9	79 (74–83)	Independent t-test / One-way ANOVA	0.22

Table 3: In Vitro pH-Dependent Drug Release Profile at 24 Hours

pH Condition	Cumulative Drug Release (%) Mean ± SD	Median (IQR)	Statistical Test	p-value

pH 7.4	28.7 ± 4.5	29 (25–32)	Repeated-measures ANOVA	<0.001
pH 6.5	54.3 ± 6.2	55 (50–59)	Repeated-measures ANOVA	<0.001
pH 5.5	71.6 ± 7.8	73 (66–78)	Repeated-measures ANOVA (Bonferroni post-hoc)	<0.001

Table 4: Stability Assessment of Nanocarriers During Storage

Parameter	Baseline Mean ± SD	End of Study Mean ± SD	Statistical Test	p-value
Particle size (nm)	182.6 ± 21.4	184.1 ± 22.0	Paired t-test	>0.05
PDI	0.24 ± 0.05	0.25 ± 0.06	Paired t-test	>0.05
Zeta potential (mV)	−21.8 ± 3.6	−21.5 ± 3.8	Paired t-test	>0.05

DISCUSSION

In this study, we successfully designed and evaluated pH-responsive biopolymer nanocarriers for targeted delivery of anticancer agents. The nanocarriers exhibited favourable physicochemical properties, effective drug loading, and enhanced drug release under acidic conditions characteristic of tumor microenvironments. A critical requirement for nanoparticle success in cancer therapy is an optimal size distribution that facilitates tumor accumulation via the enhanced permeability and retention (EPR) effect. In the present work, the mean particle size of the nanocarriers was **182.6 ± 21.4 nm**, with uniform distribution (median 179 nm, IQR: 168–196 nm) and narrow PDI (0.24 ± 0.05, median 0.23), indicating good colloidal homogeneity. Zeta potential measurements showed a moderately negative surface charge (−21.8 ± 3.6 mV), supporting aqueous stability.These characteristics are consistent with those reported for other pH-responsive polymeric carriers that achieved high stability at physiological pH while retaining responsiveness in acidic environments. Palanikumar *et al.* described ATRAM-functionalized PLGA-BSA nanoparticles with similar dimensional stability and controlled pH responsiveness, where surface functionalization influenced both size and zeta potential to optimize tumor targeting and internalization[26]. The uniform size distribution and colloidal stability observed in our formulation align with the broader consensus in the field that nanoparticle size between ~100–200 nm is optimal for exploiting the EPR effect and reducing rapid systemic clearance[27].

Effective drug delivery requires not only stable nanocarriers but also high drug loading and encapsulation efficiency to ensure sufficient therapeutic payload. Our nanocarriers demonstrated a mean drug loading capacity of 8.6 ± 1.3% and an encapsulation efficiency of 78.4 ± 6.9% (median 79%), with no significant batch-to-batch variation.

This encapsulation efficiency is comparable to values reported for other pH-responsive polymeric systems. For instance, in chitosan-based pH-responsive nanoparticles loaded with lapatinib, encapsulation efficiencies up to 75.8% were reported, along with improved cellular uptake and tumor specificity[28]. Similarly, a recent study on pegylated chitosan nanoparticles achieved encapsulation efficiency near 80% with sustained acidic pH release, highlighting that high encapsulation efficiencies are achievable with carefully engineered polymer matrices[29]. Thus, the encapsulation efficiency observed in our study is well within the range of effective drug delivery systems and suggests that our biopolymer formulation can successfully incorporate anticancer agents while maintaining stability and payload integrity.

One of the major findings of the current work was the significant enhancement of drug release under acidic conditions: cumulative release increased from 28.7 ± 4.5% at physiological pH (7.4) to 54.3 ± 6.2% at pH 6.5 and 71.6 ± 7.8% at pH 5.5 ($p < 0.001$).This pH-responsive release behavior corroborates a central principle of tumor-targeted delivery—that nanocarriers should remain stable in systemic circulation but rapidly release their cargo within the acidic tumor microenvironment. Such behavior has been extensively documented in the literature; for example, pH-responsive nanoplatforms designed for targeted cancer therapy have demonstrated significantly increased drug release at tumor-like acidic pH compared to physiological pH[30]. The magnitude of release observed in our system is similar to that in other carbohydrate or polymer-based pH-sensitive systems, which are engineered to exploit the pH gradient for controlled release, resulting in improved therapeutic indices and reduced off-target toxicity[31].

The choice of biopolymer materials in our study afforded inherent advantages, including biocompatibility and the ability to undergo chemical modifications to impart pH sensitivity. Reviews on pH-responsive polymer nanomaterials underscore that polymer carriers not only improve drug delivery efficiency in vivo but also reduce systemic toxicity by enabling targeted release[32]. Furthermore, the strategy of designing nanoparticles that remain stable at neutral pH but respond to acidic environments by structural changes has been widely exploited in tumor targeting. pH-responsive carriers have been shown to deliver drugs selectively and reduce adverse reactions, aligning well with our findings of rapid acidified pH-triggered release[30].

CONCLUSION

The present study developed and evaluated pH-responsive biopolymer nanocarriers for targeted anticancer drug delivery. The nanocarriers demonstrated favourable physicochemical properties, including nanoscale particle size, good stability, and high drug loading efficiency. A pronounced pH-dependent drug release pattern was observed, with enhanced drug release under acidic conditions mimicking the tumor microenvironment. This selective release indicates the ability of the system to remain stable in physiological conditions while enabling targeted drug delivery at tumor sites. Overall, the findings

highlight the potential of pH-responsive biopolymer nanocarriers as a promising platform for improving anticancer therapy and reducing systemic toxicity.

LIMITATIONS OF THE STUDY

The present study was limited to physicochemical characterization and in vitro drug release evaluation without assessing cytotoxicity using cancer cell lines. In vivo studies were not performed; therefore, biodistribution, pharmacokinetics, tumor-targeting efficiency, and systemic toxicity could not be evaluated. The research focused on a single anticancer drug and one biopolymer formulation, which may limit the generalizability of the findings. Additionally, long-term stability, immunogenicity, and large-scale production feasibility were not assessed. Further in vitro and in vivo studies are required to validate the clinical applicability of the developed nanocarrier system.

REFERENCES

1. Chabner BA, Roberts TG. Chemotherapy and the war on cancer. *Nat Rev Cancer*. 2005;5:65–72.
2. Cheung-Ong K, Giaever G, Nislow C. DNA-damaging agents in cancer chemotherapy. *Chem Biol*. 2013;20:648–659.
3. Maeda H, Khatami M. Analyses of repeated failures in cancer therapy for solid tumors. *Clin Transl Med*. 2018;7:11.
4. Szakács G, Paterson JK, Ludwig JA, Booth-Genthe C, Gottesman MM. Targeting multidrug resistance in cancer. *Nat Rev Drug Discov*. 2006;5:219–234.
5. Lage H. An overview of cancer multidrug resistance. *Cell Mol Life Sci*. 2008;65:3145.
6. Peer D, Karp JM, Hong S. Nanocarriers as an emerging platform for cancer therapy. *Nat Nanotechnol*. 2007;2:751–760.
7. Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer nanomedicine: progress, challenges and opportunities. *Nat Rev Cancer*. 2017;17:20–37.
8. Patra JK, Das G, Fraceto LF. Nano-based drug delivery systems. *J Nanobiotechnol*. 2018;16:71.
9. Baetke SC, Lammers T, Kiessling F. Applications of nanoparticles for diagnosis and therapy of cancer. *Br J Radiol*. 2015;88:20150207.
10. Naseri N, Ajorlou E, Asghari F, Pilehvar-Soltanahmadi Y. Nanoparticle-based contrast agents in medical imaging. *Artif Cells Nanomed Biotechnol*. 2018;46:1111–1121.
11. Fang J, Nakamura H, Maeda H. The EPR effect. *Adv Drug Deliv Rev*. 2011;63:136–151.
12. Wilhelm S, Tavares AJ, Dai Q, Ohta S, Audet J, Dvorak HF, *et al.* Analysis of nanoparticle delivery to tumours. *Nat Rev Mater*. 2016;1:16014.
13. Rosenblum D, Joshi N, Tao W, Karp JM, Peer D. Progress and challenges towards targeted delivery of cancer therapeutics. *Nat Commun*. 2018;9:1–12.
14. Barua S, Mitragotri S. Challenges associated with nanoparticle penetration. *Nano Today*. 2014;9:223–243.
15. Su YL, Hu SH. Functional nanoparticles for tumor penetration. *Pharmaceutics*. 2018;10:193.
16. Bazak R, Houri M, El Achy S, Kamel S, Refaat T, *et al.* Cancer active targeting by nanoparticles: a comprehensive review of literature. *J Cancer Res Clin Oncol*. 2015;141(5):769-784.
17. Zhang X, Lin Y, Gillies RJ. Tumor pH and its measurement. *J Nucl Med*. 2010;51:1167–1170.
18. Shen Y, Tang H, Radosz M, Van Kirk E, Murdoch WJ. pH-responsive nanoparticles for cancer drug delivery. *Methods Mol Biol*. 2008;437:183-216.
19. Kinoh H, Miura Y, Chida T, Liu X, Mizuno K, Fukushima S, *et al.* Nanomedicines eradicating cancer stem-like cells in vivo by pH-triggered intracellular cooperative action of loaded drugs. *ACS Nano*. 2016;10(6):5643-5655.
20. Najahi-Missaoui W, Arnold RD, Cummings BS. Safe nanoparticles. *Int J Mol Sci*. 2021;22:385.
21. Wolfram J, Zhu M, Yang Y, Shen J, Gentile E, Paolino D, *et al.* Safety of nanoparticles in medicine. *Curr Drug Targets*. 2015;16(14):1671-1681.
22. Jeong WJ, Bu J, Kubiatowicz LJ, Chen SS, Kim Y, Hong S, *et al.* Peptide-nanoparticle conjugates: a next generation of diagnostic and therapeutic platforms? *Nano Converg*. 2018;5:38.
23. Gilleron J, Querbes W, Zeigerer A, Borodovsky A, Marsico G, Schubert U, *et al.* Image-based analysis of lipid nanoparticle-mediated siRNA delivery, intracellular trafficking and endosomal escape. *Nat Biotechnol*. 2013;31(7):638-646.
24. Nel AE, Madler L, Velegol D, Xia T, Hoek EMV, Somasundaran P, *et al.* Understanding biophysicochemical interactions at the nano-bio interface. *Nat Mater*. 2009;8(7):543-557.
25. Liu B, Thayumanavan S. Encapsulation stability in serum. *Biomacromolecules*. 2017;18:4163–4170.
26. Palanikumar L, Al-Hosani S, Kalmouni M, Nguyen VP, Ali L, Pasricha R, *et al.* pH-responsive high stability polymeric nanoparticles for targeted delivery of anticancer therapeutics. Commun Biol. 2020;3(1):95.
27. AlSawaftah NM, Awad NS, Pitt WG, Husseini GA. pH-Responsive Nanocarriers in Cancer Therapy. Polymers (Basel). 2022;14(5):936.
28. Bhattacharya S. pH-responsive chitosan nanoparticles loaded with lapatinib trigger apoptosis

and inhibit P-gp activity in HCT116 and SW480 colorectal cancer cells. *Carbohydrate Polymer Technologies and Applications.* 2025;11:100982.

29. Alipour S, Aghamaali MR, Mahdavi A. Development of a pH-responsive pegylated chitosan nanocarrier for targeted delivery of 17-AAG and synergistic therapy in HER2+ breast cancer. *Sci Rep*. 2026;16(1):909.
30. Liu Y, Si L, Jiang Y, Jiang S, Zhang X, Li S, *et al.* Design of pH-Responsive Nanomaterials Based on the Tumor Microenvironment. *Int J Nanomedicine*. 2025;20:705-721.
31. Zhao N, Shi Y, Liu P, Lv C. pH-responsive carbohydrate polymer-based nanoparticles in cancer therapy. *Int J Biol Macromol*. 2025;306:141236.
32. Chu S, Shi X, Tian Y, Gao F. pH-Responsive Polymer Nanomaterials for Tumor Therapy. *Front Oncol*. 2022;12:855019.
33. Pilch J, Potęga A, Kowalczyk A, Kasprzak A, Kowalik P, Bujak P, *et al.* pH-Responsive Drug Delivery Nanoplatforms as Smart Carriers of Unsymmetrical Bisacridines for Targeted Cancer Therapy. *Pharmaceutics*. 2023;15(1):201.