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Evaluating the biological characteristics of targeted ZIF-8-encapsulated individual and combined drug systems for enhanced *in vivo* toxicity mitigation using folic acid ligands

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The management of toxicity, and the fulfillment of safety requirements are considered as the most prominent challenges associated with cancer drug delivery. This study introduces a novel pH-responsive nanoparticle system based on ZIF-8 for the co-delivery of a ruthenium(II) polypyridyl complex (RuPIP) and olaparib (Olap), which is designed for enhanced therapeutic efficacy and reduced systematic toxicity. To improve their biocompatibility and targeting, the nanoparticles were surface-coated with folic acid ligand, yielding the final RuPIP–Olap@ZIF-8-FA formulation. The RuPIP–Olap@ZIF-8 nanoparticles were fabricated through a rapid, eco-friendly method, and they achieved high co-loading capacities of 20.59% ± 1.38% for RuPIP and 10.77% ± 1.00% for Olap, as confirmed by HPLC analysis. *In vitro*, the FA-coated dual-drug system exhibited clear pH-responsive behaviour, releasing 80% of RuPIP and 99% of Olap at pH 5.0, compared with 32% and 29%, respectively, at pH 7.4 within 48 hours. The FA-coated RuPIP–Olap@ZIF-8 system also showed markedly enhanced cytotoxicity against the MCF-7 and MDA-MB-231 cell lines, reducing the cell viability to 11.38% and 13.48%, respectively. In comparison to the non-coated dual-drug system, the FA-coated dual-drug system did not induce lethality to 75% of embryos (LC₅₀ > 250 µg mL⁻¹) with significant improved survivability (90%) until 120 h of incubation. Results showed that RuPIP–Olap@ZIF-8-FA did not cause significant malformations, even at elevated concentrations, and did not present aggregation issues toward healthy embryos. These findings establish RuPIP–Olap@ZIF-8-FA as a promising dual-drug nanocarrier capable of targeted delivery, pH-triggered release, and distinct therapeutic pathways. Its high loading efficiency, simplicity, and improved safety profile highlight its strong potential for advancement toward clinical translation.

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1 Introduction

Combination therapy has emerged as a cornerstone in modern cancer management, offering significant advantages over monotherapy, which often suffers from limited efficacy and rapid development of drug resistance. By co-administering two or more therapeutic agents with distinct mechanisms of action, combination therapy can produce synergistic anticancer effects, reduce the required dose of individual drugs, minimize systemic toxicity, and improve patient tolerability.^{1,2} Researchers have strived to enhance drug design by integrating active targeting strategies that capitalize on the overexpression of specific molecules, thereby improving cellular uptake, targeting precision, and therapeutic outcomes.³ In contrast to conventional chemotherapy, targeted therapies and nano-scale delivery systems are recognized as superior alternatives for drug administration due to their pivotal role in cancer treatment. These nanocarriers provide a promising approach for addressing cancer-related challenges by facilitating tumor-specific drug deposition⁴ while

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diminishing adverse effects, ultimately leading to the development of more personalized treatment regimens.⁵

Metal organic frameworks (MOFs) provide a versatile drug delivery platform with high loading capacity, improved stability, enhanced solubility, controlled release, and stimulus responsiveness, promising personalized medicine and better patient outcomes due to their tunability and functionalization capabilities.⁶

MOFs are well-known in coordination chemistry and solid-state/zeolite chemistry, being classified as coordination polymers due to their formation through the bonding of metal ions (connectors) with organic ligands (linkers).⁷ The coordination bonds present in MOFs exhibit sensitivity to external pH. These bonds undergo protonation and subsequent disruption under external acidic pH conditions, and tumor tissue exhibits a comparatively acidic nature owing to aberrant cell proliferation, thereby creating an acidic environment conducive to the localized release of anti-cancer agents.⁸

MOFs are considered promising drug carriers and have enormous merits. Firstly, MOFs can interact with guest molecules through linkers or metal clusters. When drug or agent molecules are smaller than the pore volume of MOFs, they can penetrate and be efficiently stored in the pores of MOFs. Secondly, drugs can be rapidly loaded within the structure of MOFs through a variety of interactions, including electrostatic adsorption, coordination, and π - π stacking. Thirdly, MOFs prevent early drug leakage as drug molecules with specific groups can further create more stable covalent/dynamic interactions with their functional linkers. Finally, larger payloads, including nucleic acids, peptides, and proteins, can be included in the framework and provide higher stability and better tailorability.⁹

Zeolite imidazole framework (ZIF-8) is a member of the MOF family with excellent pH responsivity. ZIF-8, which is assembled from zinc ions (Zn^{2+}) and 2-methylimidazole (2-MIM), has demonstrated the ability to effectively encapsulate various substances such as proteins, nucleic acids, and drugs under mild conditions.¹⁰ Furthermore, the ligand of ZIF-8, 2-methylimidazole, undergoes protonation in the weakly acidic environment of the lysosome, facilitating the release of cargo and their escape from the lysosome through the "proton sponge effect". In addition, the easy and cost-effective preparation process of ZIF-8 should be seriously considered.¹¹ Owing to their highly porous and structurally versatile nature, ZIF-8-based carriers can be incorporated with a wide range of therapeutic drugs for targeted drug delivery applications. Furthermore, they often show relatively high drug loading capacities, which remains a significant demand in the biomedical field.^{12,13}

Over the past two decades, the zebrafish model has attracted significant attention from the scientific community, expanding their applications to include studies on human diseases, cancer, and immunology, which were previously investigated using murine models.¹⁴

Zebrafish is commonly utilized in both toxicological and immunological investigations due to its minute size, facile reproduction capabilities, elevated spawning rate seen through embryos, and noteworthy genomic and immunological likeness

to humans. Compared with traditional model animals, zebrafish embryos are characterized by small size, rapid development, and optical translucency during early development, allowing for live imaging at the organism level.^{15,16} Also, zebrafish is widely used in biological research by coupling with a large number of fluorescent transgenic lines. Vascular formation *in vivo* can be visualized directly to greatly improve the understanding of vascular biology.^{17,18}

The zebrafish genome shares approximately 87% homology with the human genome, and its signal transduction pathway, physiological structure, and functions closely resemble those of mammals. In contrast to *in vitro* toxicity evaluations, conducting *in vivo* toxicity studies using zebrafish embryos, whether larvae or adults, allow for a more accurate reflection of the absorption, distribution, metabolism, and excretion of tested substances within a living organism.¹⁹ Also, they resemble the physiological, genetic, vascular, brain, and immune system of humans.²⁰

The present system offers numerous advantages including the ability to conduct investigations utilizing various techniques for inducing cancer in zebrafish. Furthermore, it explores methods for assessing cancer development within the system, and testing the toxicity of anticancer drugs and NPs. The RuPIP-Olap@ZIF-8-FA system was synthesized by employing a one-pot method. Despite the potential risks posed by this substance to human health and the environment, the current knowledge in this area remains limited. Thus, this study aimed to expose zebrafish to ZIF-8 at concentrations ranging from 15.60–1000 $\mu\text{g mL}^{-1}$ over a period of five days.

The properties and potential applications of ruthenium(II) polypyridyl complexes (RuPIP) are studied due to their demand in medicine, with particular emphasis on their anticancer activity. Various ruthenium compounds have been evaluated as potential anticancer agents in clinical trials²¹ due to their extraordinary characteristics including good biocompatibility and low toxicity towards normal cells.²² These complexes have also shown promising outcomes in overcoming drug resistance, which is believed to be attributed to their comparatively slow rate of ligand dissociation *in vivo*, resulting in the more controlled release of the active drug species.²³

Poly (ADP-ribose) polymerase (PARP) plays a crucial role in cellular repair processes and cell division. Thus, PARP inhibitors have shown effectiveness in the treatment of cancer by impeding the repair mechanisms of cancerous cells, ultimately leading to their demise.²⁴ The first PARP inhibitor, olaparib, was authorized by the FDA in 2014 for the treatment of high-grade serous ovarian cancer.^{25,26} Olaparib (PARP inhibitor) was evaluated in clinical trials, both as mono and combination therapy.

The employment of a combination of various chemotherapeutic agents is efficient in preventing the development of drug resistance, minimizing systematic toxicity, reducing the risk of tumor recurrence, and mitigating the adverse effects associated with prolonged exposure to a single chemotherapeutic agent.^{27,28} In summary, the development of nanocarriers is engineered with the goal of augmenting the cytotoxic effect of chemotherapy drugs.²⁹



Among the available nanocarriers, folic acid-coated nanocarriers have demonstrated exceptional efficacy for specific targeting, owing to their promising selectivity for overexpressed folate receptors on the surface of breast cancer cells. Because folate-coated nanocarriers are target-specific, drug internalization in breast cancer cells is significantly improved, and its accumulation in non-target organs is further reduced.³⁰ Folic acid (FA) molecules possess a distinctive capacity to selectively bind to the overexpressed FA receptor located on the plasma membrane of a multitude of cancer cells,³¹ including those originating from breast, ovarian, lung, kidney, and epithelial tissues. This characteristic allows folate-tagged nanocarriers to specifically target cancer cells.³² In non-cancerous tissue cells, folate is internalized *via* carrier proteins such as the transmembrane-reduced folate carrier, which is widely present in normal tissues as well as malignant tumors, or through the proton-coupled folate transporter in low pH environments, such as the intestine, followed by membrane-bound FR.³³ Conversely, in cancer cells, the folate receptors situated on the cell surface recognize and form complexes with folate, thereby initiating the formation of endocytic vesicles for cellular internalization, which serves as the primary mechanism for folate molecules to gain entry into cancerous cells. The distinct modes of folate entry into normal *versus* tumor cells offer an opportunity to modify folate onto the surface of carriers as a targeting moiety, facilitating the selective transport of drug delivery systems into tumor cells and enabling the release of the loaded drug within the cytoplasm to exert its anti-cancer effects in the field of biomedicine, thereby achieving targeted therapeutic outcomes for tumors.^{34,35} Thus, the coating or conjugation of ZIF-8 with FA (an active targeting ligand) can facilitate the delivery of drugs to the target site and reduce the damage to normal tissues and cells.

In contrast with previous studies that employed complex or multi-step functionalization approaches, this work introduces a streamlined and cost-effective method for the synthesis of FA-physical surface coated ZIF-8 encapsulating RuPIP and Olaparib within its structure. The novelty of this work not only demonstrates a high drug-loading efficiency and pH-responsive release, but also lies in the systematic evaluation of the cytotoxicity and IC₅₀ values of this specific combination within the chosen ZIF-8 carrier, which has not been extensively studied in the context of breast cancer (to the best of our knowledge). Moreover, the achieved findings demonstrate an improved therapeutic index and reduced toxicity to normal cells, suggesting that even well-known drugs, when delivered *via* a biocompatible and tunable ZIF-8 system, can yield significant therapeutic benefits. Furthermore, the subsequent coating with folic acid as a targeting ligand leads to a significant reduction in *in vivo* toxicity, as folic acid is known to effectively mitigate the toxicity of dual-drug systems. Notably, the drug release from the RuPIP-Olap@ZIF-8-FA system is designed to ensure the rapid release of both drugs during the decomposition of the organic linker in an acidic environment, thereby enhancing the efficacy of breast cancer treatment. This system is thoroughly studied, besides a systematic investigation of its *in vitro* and *in vivo* biological effects.

2 Materials and methods

2.1 Chemical materials

Folic acid (95% purity), zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O; 99% purity), and 2-methylimidazole (99% purity) were purchased from Sigma-Aldrich. Olaparib was sourced from Med Chem Express. All chemicals used for the synthesis of ruthenium polypyridyl (RuPIP), which was synthesized in-house, were purchased from Sigma-Aldrich, Merck Germany and Thermo Fisher Scientific. All commercial reagents were utilized without purification unless otherwise specified. Phosphate-buffered saline (PBS) was purchased from Gibco. Zebrafish embryos (*D. rerio*) and media of zebrafish embryo were acquired from the Animal Care and Use Committee at the University Putra Malaysia.

Fourier transform infrared spectra were recorded using a PerkinElmer FTIR Spectrum Two spectrometer. Analytical high-performance liquid chromatography (HPLC) was performed using a PerkinElmer system at the Malaysia-Japan International Institute of Technology (MJIT), Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia. The analysis utilized a C18 analytical column, with the mobile phase consisting of a mixture of acetonitrile, methanol and water with ammonium acetate in a ratio of (60:20:20 v/v), and the flow rate was maintained at 1.2 mL min⁻¹. The detection wavelength was set at 276 nm for both drugs. Under the chromatography conditions, the retention time of RuPIP was 4.2 min and 1.5 min for Olaparib.

2.2 Synthesis of coated dual-drug nanoparticle system

Ruthenium polypyridyl (RuPIP) was in-house-synthesized, as outlined previously in the literature.³⁶ The encapsulation of dual-drug RuPIP and olaparib within the ZIF-8 structure was performed following the same procedure as previous research.³⁷ Approximately 20 mg of the combination nanoparticle system was weighed and prepared for the subsequent step.

The coated of the dual-drug system was accomplished by modifying RuPIP-Olap@ZIF-8 through slight adjustment of a previously documented reaction. A total of 20 mg of RuPIP-Olap@ZIF-8 nanoparticles was dispersed in 2 mL of ethanol, followed by the addition of 1.0 mL of folic acid (FA) solution (20 mg mL⁻¹, pH = 7.0). The mixture was agitated for a few minutes using a pipette, and subsequently subjected to ultrasonic treatment at room temperature for 2–3 min.³⁸ The resulting RuPIP-Olap@ZIF-8-FA nanoparticles were isolated *via* centrifugation at 10 000 rpm, washed with ethanol, and dried in an oven at 40 °C. Our prior publication offers a comprehensive account of the fabrication and features of the cancer-targeting nanotherapeutic RuPIP-Olap@ZIF-8-FA, non-targeting RuPIP-Olap@ZIF-8, and the pure nano-zeolitic imidazolate framework-8 (ZIF-8) utilized in this study.

2.3 The drug release profile of RuPIP-Olap@ZIF-8-FA

The dissolution study of both drugs, RuPIP and Olaparib, was conducted in PBS dissolution media using dialysis under human conditions of ±37 °C with gentle stirring (100 rpm). The



nanotherapeutics were collected and analysed at specific time intervals (2, 4, 6, 24, and 48 hours). HPLC was conducted at a wavelength of 271 nm, utilizing a mobile phase composed of acetonitrile, methanol and water along with a buffer, in a ratio of (60 : 20 : 20 v/v) and a flow rate of 1 mL min⁻¹. The dissolution percentage of RuPIP and Olap was determined based on the ratio of released amount to the total loaded amount of both drugs, assessed at pH levels of 7.4 and 5.0.

2.4 Structure characterization of dual-drug nanoparticle system

The functional groups within the materials were analysed using a Nicolet 6700 FTIR-ATR spectrophotometer. Spectra were recorded over the wavenumber range of 4000 to 400 cm⁻¹. Prior to sample placement, the surface of the stage was cleaned with 70% ethanol and lint-free wipes. Each sample, weighing 1 g, was positioned on the diamond stage and subjected to compression using a pressure clamp while data collection was conducted. The morphology of the synthesized nanoparticles (NPs) was examined using a transmission electron microscope (TEM). A Zeiss transmission electron microscope operating at 100.0 kV was employed to evaluate the particle size and structure of the samples. The TEM grids were subsequently scanned at 200 kV to capture the images. The X-ray diffraction (XRD) study was performed using a XRD Shimadzu 6000 instrument (Kyoto 604-8511, Japan), while structure morphological and particle size evaluation was conducted *via* scanning electron microscopy (FE-SEM; Nova™ Nano SEM 450). Furthermore, thermogravimetric analysis (TGA) of the materials was performed using a PerkinElmer STA6000 thermal analysis system. Samples weighing 25 mg were placed in an alumina pan and heated from 50 °C to 800 °C at a rate of 10 °C min⁻¹ under a continuous flow of nitrogen gas (N₂).

2.5 Biological assessment of all nanoparticle systems on embryonic zebrafish

2.5.1 Sample preparations. Stock solutions of five samples, pure (ZIF-8) carrier, RuPIP@ZIF-8, Olap@ZIF-8, RuPIP-Olap@ZIF-8, and RuPIP-Olap@ZIF-8-FA, were prepared at a concentration of 200 000 µg mL⁻¹ by dissolving the samples in 100% dimethyl sulfoxide (DMSO). Then, a working solution then created by diluting the stock solution 200-fold in embryo media (Danio-Sprint solution), achieving a final concentration of 1000 µg mL⁻¹ and 0.5% DMSO. Subsequently, the samples were subjected to 2-fold serial dilution in embryo media to generate seven concentrations ranging from 15.63–1000 µg mL⁻¹ in a 96-well microplate. A previous study indicated that there is no increase in lethality or malformations with DMSO concentrations up to 1%.³⁹ Therefore, embryos in embryo media containing 0.5% DMSO served as the control group.

The embryos were examined using an inverted light microscope (Nikon Eclipse TS100) to ensure that only viable and healthy specimens were selected for subsequent evaluations, which included assessments of permeability, toxicity, malformation, and hatching rate. All nanoparticle systems were administered to the zebrafish embryo toxicity assay through

incubation in 96-well round-bottom plates. The zebrafish embryo test was conducted in accordance with Test No. 236: Fish Embryo Acute Toxicity Test (FET), which allows for the assessment of phenotypes exhibited by embryos following chemical exposure. Healthy embryos at 24 hpf were transferred to a 96-well, with one embryo per well, and maintained at room temperature.

Then, the zebrafish embryos were exposed to the RuPIP-Olap@ZIF-8-FA targeting system and a range of other nanoparticle systems for a duration of 120 hours, with concentrations varying from 0 (control) to 1000 µg mL⁻¹. Observations and scoring were performed in comparison to the control group. Key parameters for assessing lethality in the embryos or larvae included mortality, coagulation of embryos, absence of somite formation, non-detachment of the tail, and lack of heartbeat.

The lethal concentration (LC₅₀) was calculated using the GraphPad Prism 8.0 software. Finally, the hatching rate was determined using the following formula:⁴⁰

$$\text{Hatching rate (\%)} = \left[\frac{\text{number of hatched embryos}}{\text{initial number of embryos}} \right] \times 100$$

All statistical analyses for the experiments described above were analysed using GraphPad Prism 8.0. Error bars represent the mean values with standard deviation (SD) unless otherwise specified. The statistical significance level was set at $P > 0.005$.

2.6 Cell culture

The MCF-7 and MDA-MB-231 breast cancer cell lines were cultured in DMEM supplemented with 10% fetal bovine serum (FBS) and 1% penicillin/streptomycin antibiotic. The HaCaT normal cell line was cultured in DMEM, maintaining the same percentage of cancer cells. Both cell types were kept at 37 °C in a humidified atmosphere with 5% CO₂ and were routinely subcultured using trypsin.

2.6.1 MTT assay. Cells were seeded in 96-well plates at a density of 5×10^3 cells per well for MCF7 cells, 4×10^3 cells per well for MDA-MB-231 cells, and 7.5×10^3 cell per well for HaCaT cells. After allowing for 24 hours of adherence, the cells were treated according to the protocols outlined in the main text. Following the treatment, the solutions were removed, and thiazolyl blue tetrazolium bromide (MTT) reagent was added to the cells at a concentration of 0.5 mg mL⁻¹. Then, the cells were incubated for four hours. Subsequently, the reduced purple formazan crystals were solubilized with 100 µL of dimethyl sulfoxide (DMSO), and the absorbance was measured at 570 nm, using a reference wavelength of 620 nm, with a microplate reader. The average percentage reduction in cell viability was calculated relative to the untreated control cells and graphed using the GraphPad Prism software.

2.6.2 Apoptosis annexin V-FITC/PI assay. Flowcytometry with the FITC-annexin V/PI apoptosis detection kit was used to assess the impact of the combined system RuPIP-Olap@ZIF-8 and targeted system RuPIP-Olap@ZIF-8-FA on apoptosis. Cells (3×10^5) were seeded in 6-well plates and incubated at 37 °C



C for 24 hours. After treatment, the cells were trypsinised, washed twice with PBS, and then incubated with 500 μL of $1\times$ binding buffer and 5 μL annexin V-FITC for 20 min at room temperature. Prior to analysis, a 5 μL drop of PI ($20\text{ }\mu\text{g mL}^{-1}$) was added. Flow cytometric analysis was conducted using a flow cytometer, with the findings analysed using the NovoExpress software, counting a minimum of 10 000 cells per sample.

3 Result and discussion

3.1 FTIR and XRD diffraction analysis

The FTIR spectrum of ZIF-8, as shown in Fig. 1, reveals absorption peaks located at 420 cm^{-1} and $1500\text{--}1350\text{ cm}^{-1}$ (ν ring), corresponding to the stretching vibration peak of the Zn–N bond and HmIM, indicating the presence of Zn^{2+} and 2-methylimidazole in ZIF-8, respectively.^{41,42} Additionally, the peaks located at 3135, 2930 and 1583 cm^{-1} are ascribed to the stretching vibrations of the aromatic and aliphatic C–H bond in 2-methylimidazole, fatty C–H bonds, the C–N and C=N bonds, respectively.⁴³

The detected signals observed at $1450\text{--}1300\text{ cm}^{-1}$ correspond to the stretching of the entire chain, while the band detected at 1144 cm^{-1} is attributed to the C–N aromatic stretching mode. Additionally, the peaks located at 997 and 755 cm^{-1} can be considered as the C–N bending vibration and C–H bending phase, respectively.

We can conclude that there is no characteristic group of RuPIP, while Olap is found in the FTIR spectra of RuPIP@ZIF-8, Olap@ZIF-8 and RuPIP-Olap@ZIF-8, and these results indicate the absence of a characteristic absorption band corresponding to the free drugs, suggesting their successful encapsulation within the ZIF-8 framework. Also, this suggests that the individual and combination of drugs did not alter the chemical structure of ZIF-8 and that they were loaded in the pores of ZIF-8, which are wrapped in the pores and pore wall without resting on the surface. These findings are in agreement with that reported previously.⁴⁴

The band observed at 683 cm^{-1} corresponds to the out-of-plane bending vibration of the 2-methylimidazole ring. The

strong bending vibrations at 755 cm^{-1} and 1378 cm^{-1} are linked to the imidazole ring. Furthermore, the C=N stretching vibration is identified at 1578 cm^{-1} , and the band at 423 cm^{-1} is assigned to Zn–N stretching.⁴⁵

Encapsulation of the drug within the ZIF-8 framework provides additional protection for the drug from environmentally induced degradation.⁴⁶

The peak observed at 1030 cm^{-1} can be attributed to the C–O and C–O–C stretching vibrations, which are characteristic of FA, within the RuPIP-Olap@ZIF-8-FA framework. Additionally, the peak detected at 1750 cm^{-1} corresponds to the C=O stretching vibration of the amide group associated with the alpha carboxyl group of FA. Notably, this peak exhibits a shift relative to the corresponding band of free FA at 1693 cm^{-1} , which is due to the interactions between FA and components of the framework.⁴⁷ Analysis of the FTIR spectrum of folic acid revealed characteristic peaks in the range of $3000\text{--}3500\text{ cm}^{-1}$, corresponding to the stretching vibration of the –OH functional groups within the pterinic and glutamic acid portion. Furthermore, a distinct carbonyl stretching vibration was clearly observed at 1602 cm^{-1} . The absorption band observed at 1600 cm^{-1} is attributed to the bending vibrations of –NH groups, while the band at 1493 cm^{-1} is likely associated with the C–C stretching vibrations within the pterinic ring.⁴⁸

In the FTIR spectrum of RuPIP-Olap@ZIF-8-FA, the absorption bands of ZIF-8, as well as the appearance of an amide –CONH band at 1692 cm^{-1} and –NH bending vibrations at 1572 cm^{-1} all provide evidence for the successful conjugation of the –COOH group of folic acid (FA) with the –NH₂ groups present on ZIF-8.⁴⁹

The loading of the drug(s) was determined by high-performance liquid chromatography (HPLC) at a wavelength of 276 nm in previous work. The results indicated that the individual loading capacities of RuPIP and Olap within the ZIF-8 framework were approximately $23.31\% \pm 7.27\%$ and $12.66\% \pm 4.02\%$, respectively. In contrast, the combined loading capacities for RuPIP and Olap were approximately $20.59\% \pm 1.38\%$ and $10.77\% \pm 1.00\%$ for RuPIP and Olap, respectively.⁵⁰

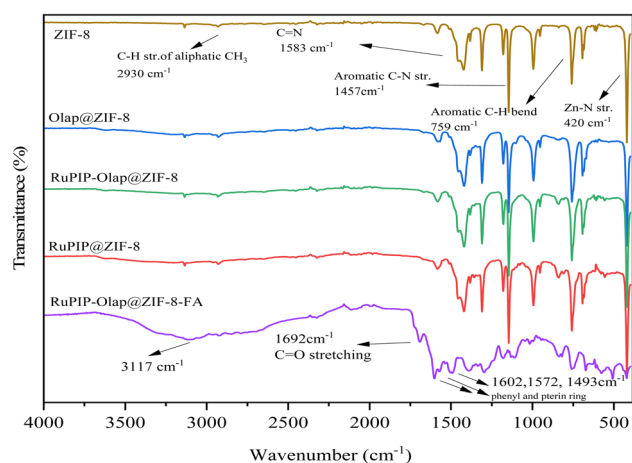


Fig. 1 Comparison of the Fourier-transform infrared spectra of all the nanoparticle systems.

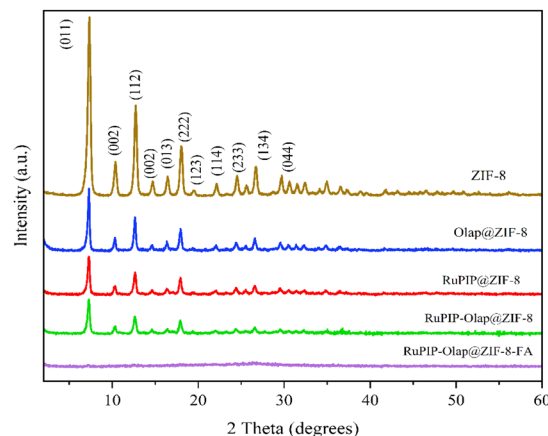


Fig. 2 XRD patterns of pure synthesized ZIF-8, RuPIP@ZIF-8, and Olap@ZIF-8 nanoparticles compared with co-loaded drug RuPIP-Olap@ZIF-8 nanoparticles.⁵⁰



To analyse the crystal structure of all the synthesized nanoparticle systems in detail, powder X-ray diffraction was conducted, and all the findings are presented in Fig. 2. The detected peaks observed in the ZIF-8 spectrum at 2θ angles of 7.3° , 10.3° , 12.7° , 14.6° , 16.4° , 18.0° , 22.1° , 24.4° , 26.6° , 29.6° , and 32.3° are attributed to the (011), (002), (112), (022), (013), (222), (114), (233), (134), (044), and (235) crystal planes of ZIF-8, respectively, and matched well with the reported literature. ZIF-8 demonstrated different peaks with a narrower width, which can be

attributed to its smaller crystal size and uniform morphology, suggesting an enhancement in its crystallinity.⁵⁰ These results are in accordance with the standard diffraction patterns recorded in JCPDS Card No. 00-062-1030.⁵¹

The results are consistent with previous reports, as no impurity peaks were detected in the XRD planes, indicating that the preparation process yielded highly pure and crystalline ZIF-8.⁵² No alteration in the XRD pattern was observed for any of the drug-loaded ZIF-8 samples compared to the pure ZIF-8. Also,

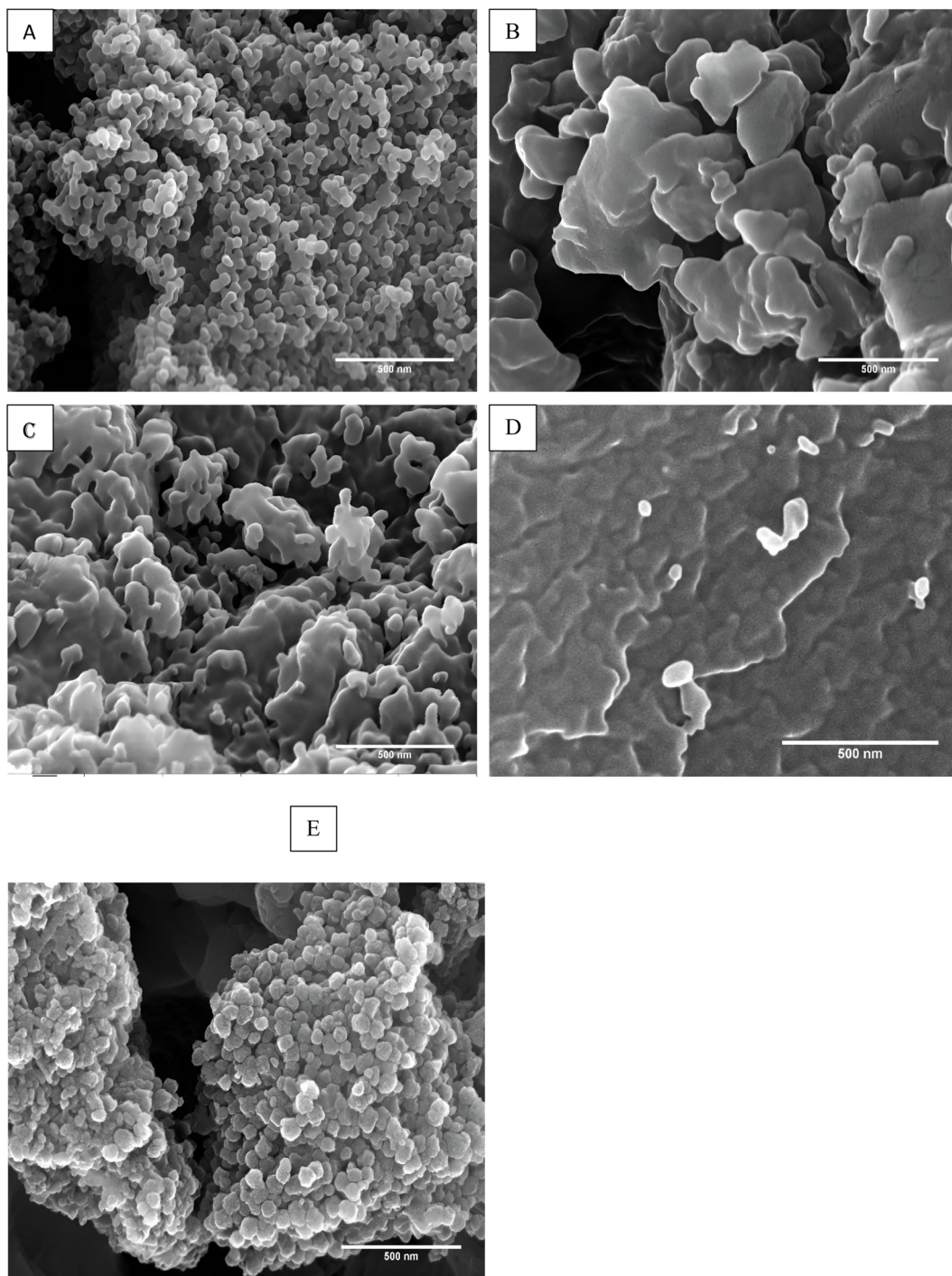


Fig. 3 SEM images of (A) ZIF-8 nanoparticles, (B) RuPIP@ZIF-8, (C) Olap@ZIF-8, (D) RuPIP-Olap@ZIF-8 and (E) RuPIP-Olap@ZIF-8-FA.

this indicates that the ZIF-8 framework is stable and the encapsulation process has minimum impact on its crystallinity.⁵³ Also, the XRD pattern of the coated system, RuPIP-Olap@ZIF-8-FA nanoparticles, revealed the completed disappearance of all the ZIF-8 peaks and no obvious peak related to ZIF-8 was observed.

3.2 Transmission electron microscopy and scanning electron microscopy analysis

The transmission electron microscopy (TEM) and field emission scanning electron microscopy (FE-SEM) images were used to study and evaluate the shape and structure of the ZIF-8 particles. The morphology studied using SEM of pure ZIF-8 produced an image showing typical, uniform-sized, bigger particles crystallites⁵⁴ with a hexagonal shape. These results are comparable with a previous report showing a uniform particle size distribution below 250 nm, consistent with the size range determined by SEM analysis.^{55,56} The FE-SEM images at a scale of 500 nm are depicted in Fig. 3. The TEM measurements demonstrate the successful synthesis of pure ZIF-8 as well, displaying a near-perfect hexagonal form and these results are in agreement with the SEM findings. The TEM analysis was conducted to confirm the successful coating of folic acid on the outer surface of RuPIP-Olap@ZIF-8. As illustrated in Fig. S1(E), after coating with FA, the bulk morphology of the co-drug nanoparticle system was uniform with an agglomerated flower-like morphology. The system was entirely transferred from a uniform structure to an aggregated structure, confirming that FA had coated the nanoparticles both within and outside of the dual system.

The image of the final structure of the coated dual-drug system with folic acid showed that it possessed a polyhedral morphology with an average diameter of about 175.13 ± 4.74 nm according to the results presented in Table 1.

The true nanoparticle size is more accurately determined using the SEM or TEM technique, which enables the direct visualization and precise measurement of individual nanoparticle dimensions and morphology. Fig. S1(A and B) illustrate the rhombic dodecahedral three-dimensional structure of pure ZIF-8, characterized by well-defined sharp edges and twelve [110] facets, representing the most stable equilibrium morphology of ZIF-8.⁵⁷ In contrast to the well-defined structure of ZIF-8, the morphology of RuPIP-Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA appears less regular, and their angles become blurred, indicating the successful loading and surface modification of ZIF-8 with the guest molecules, as depicted in Fig. S1(E and F). Furthermore, RuPIP-Olap@ZIF-8-FA exhibits a rougher

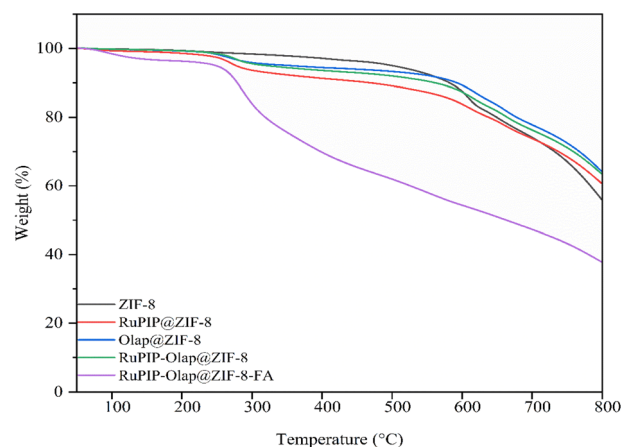


Fig. 4 TGA thermograms of pure ZIF-8 carrier, Olap@ZIF-8, RuPIP@ZIF-8, RuPIP-Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA.

surface morphology, which can be attributed to the addition of folate. Notably, the drug-loaded olaparib particles still maintain the same uniform dodecahedral structures as ZIF-8, suggesting that olaparib loading does not disrupt the microstructure of the ZIF-8 crystal. This is likely because the olaparib particles are small enough to be entrapped by ZIF-8 without disrupting its structure.

According to the TEM analysis, particle size of ZIF-8 was measured to be 68.55 ± 2.98 nm. The individual therapies displayed particle sizes of 79.56 ± 6.8 nm for Olap@ZIF-8 and 91.53 ± 5.98 nm for RuPIP@ZIF-8. In contrast, the combination therapy exhibited larger particle sizes, measuring 150.04 ± 7.35 nm for RuPIP-Olap@ZIF-8 and 183.15 ± 5.58 nm for the RuPIP-Olap@ZIF-8-FA nanocarrier. TEM provides the dry core size of the particles. The results from the TEM analytical technique yield critical insights into the physicochemical properties of these nanocarriers, which significantly influence their drug delivery performance. These properties directly affect the solubility, stability in serum, ability to penetrate cancer tissues, drug entrapment efficiency, and drug release kinetics of the nanocarriers.⁵⁸

3.3 Thermogravimetric analysis of nanoparticle system

Thermogravimetric analysis (TGA) and differential thermogravimetric (DTG) analysis were performed to study the thermal degradation behaviour of pure ZIF-8, as well as the drug-loaded ZIF-8 formulations. These techniques quantify the percentage weight loss in a sample over a specific temperature range, typically from 10–800 °C under nitrogen gas. The observed mass

Table 1 Comparison of SEM and TEM results for pure ZIF-8 and drug-loaded samples

Nanoparticle system	Particle size by TEM (nm)	Particle size by SEM (nm)
ZIF-8	68.55 ± 2.98	67.60 ± 3.25
RuPIP@ZIF-8	91.53 ± 5.98	110.67 ± 11.81
Olap@ZIF-8	79.56 ± 6.80	84.16 ± 6.63
RuPIP-Olap@ZIF-8	150.04 ± 7.35	134.93 ± 9.09
RuPIP-Olap@ZIF-8-FA	183.15 ± 5.58	175.13 ± 4.74



Table 2 Thermal decomposition analyses of the samples

Sample	Initial decomposition temperature (°C)	Initial weight loss (%)	Temperature for final decomposition (°C)	Final weight loss at 400–500 °C
ZIF-8				
RuPIP@ZIF-8	104.57	8.33	422.06	30.18
Olap@ZIF-8	175.87	5.07	412.52	29.99
RuPIP–Olap@ZIF-8	139.59	6.44	430.34	29.66
RuPIP–Olap@ZIF-8-FA	187.22	3.62	188.69	58.53

changes reflect processes such as thermal decomposition, dehydration and thermal oxidation, as shown in Fig. 4.

All systems were measured in the temperature range corresponding to the decomposition of RuPIP and Olap (180–450 °C). The TGA–DTA profiles of all the nanoparticle systems are shown in Fig. S6 and (Table 2).

The onset of the degradation of all the nanoparticle systems occurred in two stages of mass loss. The initial weight loss for the ZIF-8 nanoparticles in the first stage was 12.09 wt% within the temperature range of 110 °C to 426 °C, which is attributed to the physical adsorption of the solvent or water molecules on the surface of the nanoparticles.⁵⁹ Subsequently, the second weight loss represented degradation starting with a rapid weight loss of 33.53 wt% observed between 536–798 °C, corresponding to the elimination of the capping agent of the nanoparticle and framework degradation of the structures and complete decomposition of the organic linker imidazolate. In the higher temperature range of around 581–830 °C, it undergoes a significant weight loss, which leads to the collapse of the MOF structure.

Starting from the initial temperature to 400 °C of Olap@ZIF-8 system exhibited an initial weight loss of approximately 5.07%, which can be attributed to the removal of physically adsorbed from the ZIF-8 structure. With a further increase in temperature, the Olap@ZIF-8 profile showed a gradual weight loss of around 29.99%, as illustrated in Fig. 4. Alternatively, RuPIP@ZIF-8 showed a higher initial weight loss in the same temperature range about 8.33% and around 30.18% after 400 °C.

Notably, the TGA profile of the combination drugs when encapsulated shows a prolonged plateau above 250 °C with a minor weight loss of 6.44 wt%, and around 29.66% after 400 °C, indicating the exceptional thermal stability of the nanoparticles and serving as strong evidence of the high drug loading within ZIF-8. This is first observed as a dip in the decomposition curves of the nanoparticles with the encapsulated drugs and is attributed to the removal of ethanol present in their structure, which used as the solvent in their synthesis. It can be confirmed that the encapsulated drugs in ZIF-8 are stable up to around 250 °C. In the present work, the interaction of the ZIF-8 framework with the drug *via* one-pot synthesis was found to enhance the thermal stability of the nanoparticle system.

In comparison, the TGA profile of ZIF-8 exhibits a lower decomposition rate after heating to 536 °C. In contrast, both the Olap@ZIF-8 and RuPIP–Olap@ZIF-8 nanoparticle systems display thermal stability similar to that of pristine ZIF-8, with lower decomposition rates of 29.99 wt% and 29.66 wt%,

respectively, within the temperature range of 506–704 °C. This reduced decomposition can be attributed to the presence of adsorbed linkers and the subsequent gradual degradation of the framework beyond 704 °C. The structural integrity of nanoparticle-combined system at temperatures exceeding 800 °C begins to deteriorate, ultimately collapsing into solid oxide materials.⁶⁰ This collapse is a result of the degradation of the carbon framework within the material.⁶¹

In the final combined system coated with the targeting ligand FA, the residual mass was reduced to approximately 3.62%, which may serve as a promising indicator of effective surface coating. A sharp weight loss of 58.53% was observed between 250 °C to 750 °C, corresponding to the thermal degradation of the folate coating. This degradation occurred more rapidly than that of the combination sample, which is caused by the FA covering the combination drug loaded nanoparticles. Furthermore, the low nitrogen adsorption in RuPIP–Olap@ZIF-8-FA NPs indicates that their pores were blocked by the polymer coating, suggesting the successful coating of FA.⁵⁷

The findings are consistent with previously reported results for ZIF-8-encapsulated DAP, which exhibited a thermal degradation profile closely resembling that of pure ZIF-8. In particular, the encapsulated formulation demonstrated a more uniform heat flow compared to the unmodified ZIF-8. Additionally, no melting peak corresponding to the drug was detected in the DAP@ZIF-8 sample, indicating that the drug was molecularly dispersed within the system.⁶² These results give a good indication that the encapsulation for individual and combination drugs effectively protected the drugs against thermal degradation.

3.4 Drug release behaviour and kinetic energy analysis

The release behaviour of both drugs from the coated ZIF-8-FA system also exhibited clear pH dependence, as depicted in Fig. 5. At pH 5.0, RuPIP and Olap are released rapidly within the first few hours (8 hours), achieving the cumulative release of $80.08\% \pm 4.8\%$ of RuPIP from the coated system, and $99.68\% \pm 4.1\%$ of Olap after 48 hours of incubation. In contrast, the cumulative release at pH 7.4 is only approximately $32.69\% \pm 2.8\%$ for RuPIP and $29.65\% \pm 1.05\%$ for Olap after 48 hours. Following this, the drugs that were physically adsorbed in the nanoparticle pores diffused rapidly into the surrounding solution due to molecular motion. Eventually, the drugs adsorbed on the pore walls *via* physical adsorption and hydrogen bonding were gradually released into the solution as the organic framework collapsed.⁶³



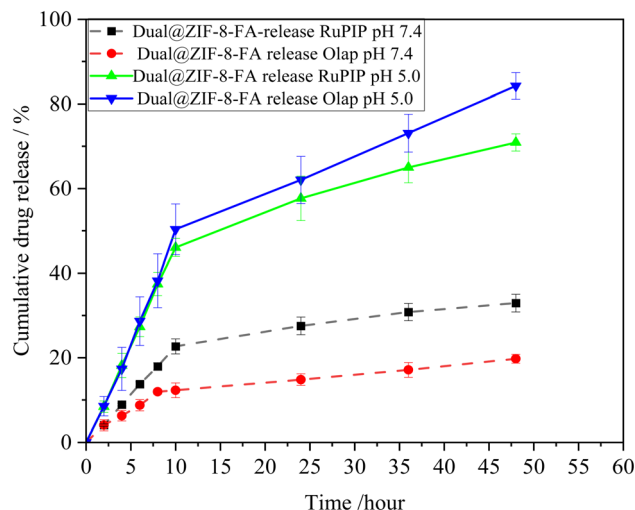


Fig. 5 Comparison of RuPIP and Olap dissolution release from combined system (RuPIP–Olap@ZIF-8) and coated combined targeting system RuPIP–Olap@ZIF-8-FA in PBS at 37 °C. (A) At pH 7.4 (represented by dashed lines) and (B) at pH 5.0 (indicated by solid lines). The values represent mean $\pm$ SD from three independent experiments ($n = 3$).

Therefore, at a pH of 7.4, the initial rapid release of both drugs within the first 8 hours can be attributed to their swift release from the pores into the solution. The subsequent slow release is likely due to the gradual diffusion of the drugs from the pore walls into the solution as the ZIF-8 framework collapses. Conversely, under acidic conditions, the drugs can be released rapidly, alongside the disintegration of the ZIF-8-FA structure. The acid-responsive release of RuPIP and Olap is dependent on the degradation of the ZIF-8 structure under acidic conditions, as previously mentioned.⁶⁴ At pH 7.4, the release of both drugs occurs slowly, whereas at pH 5.0, both the release rate and the cumulative amount of drugs significantly increase. The pH-dependent release behaviour of Zn^{2+} is attributed to the coordination bond between the Zn^{2+} ions and the ligand. In aqueous solution, the methylimidazole (MeIm) ligand loses protons (H^+), thereby facilitating coordination with excess Zn^{2+} .⁴⁷ Under acidic conditions, the ligand becomes protonated, disrupting the coordination between Zn^{2+} and MeIm and resulting in the release of Zn^{2+} .⁴⁸ The percentage of drug release was higher at pH 5.0 for both nanoparticles,

confirming the pH sensitivity of the ZIF-8 nanoparticles due to the disruption of bonds between zinc and imidazole in acidic media.⁶⁵

Various kinetic models were employed to analyse the experimental release data for both the RuPIP and Olap drugs within the final system, RuPIP–Olap@ZIF-8-FA, after being coated with folic acid. The most suitable kinetic equation was determined based on the correlation coefficients value (R^2), which accurately reflects the kinetics of drug release. The comparison of the correlation coefficients presented in Table 3 reveals that both the Higuchi and Korsmeyer–Peppas models demonstrate similar higher coefficients for both drugs within the delivery system across different pH environments. This suggests that the release of Olap and RuPIP is influenced not only by the dissolution kinetics of ZIF-8 but also the diffusion processes from the encapsulation and immobilization media. These findings agree with the study of Mi *et al.*, who found that the calculations of the cumulative release rate of the drug fit well with the Korsmeyer–Peppas model in the drug release curve.³⁴

The Higuchi and Korsmeyer–Peppas models were employed to analyse the drugs release profiles of both compounds at pH 7.4 and pH 5.0, as illustrated in Fig. S2–S5. The findings demonstrated a strong linear correlation coefficient of $R \geq 0.950$, indicating the role of diffusion in the release process. As presented in Table 3, the release constant (n) for the co-loaded@ZIF-8-FA across different pH environments exceeded 0.95, suggesting that the primary mechanism of drug release from the nanosystem is matrix erosion. Notably, the release mechanism of RuPIP–Olap@ZIF-8-FA at pH 5.0 was predominantly characterized by skeletal dissolution, whereas, at pH 7.4, the release mechanisms were identified as Fick's diffusion and erosion. Additionally, the coated system featuring the folate ligand, RuPIP–Olap@ZIF-8-FA nanoparticles, exhibited no drug leakage at the physiological pH of 7.4. These results indicate that folic acid and ZIF-8 may serve as an effective platform for the delivery of RuPIP and Olap.

3.5 Cytotoxicity analysis of targeted combined system

A cytotoxicity assay was performed using the MCF-7 and MDA-MB-231 breast cancer cell lines, as well as HaCaT normal cells. These cells were treated with various concentrations of RuPIP–Olap@ZIF-8-FA and incubated for 24 and 48 hours. The resulting cytotoxicity was assessed using the MTT assay, as

Table 3 Models fitting for coated combined targeting system release kinetics models

Correlation coefficient of model (R^2)						
pH	Formulation	Zero order	First order	Higuchi	Hixson–Crowell	Korsmeyer–Peppas
7.3	RuPIP–Olap@ZIF-8-FA (RuPIP kinetics release)	0.8646	0.8301	0.9795	0.877	0.99914
7.3	RuPIP–Olap@ZIF-8-FA (Olap kinetics release)	0.9049	0.9076	0.9907	0.9184	0.9886
5	RuPIP–Olap@ZIF-8-FA (RuPIP kinetics release)	0.9128	0.9559	0.9872	0.9592	0.9835
5	RuPIP–Olap@ZIF-8-FA (Olap kinetics release)	0.9494	0.9148	0.9712	0.9184	0.9534



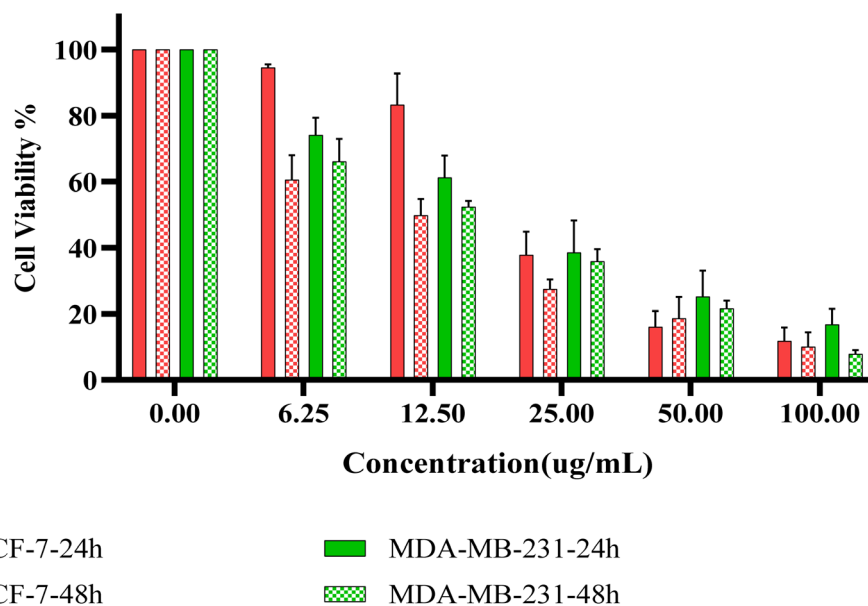


Fig. 6 Bar chart displaying the cytotoxicity effects of RuPIP–Olap@ZIF-8-FA on MCF-7 cells (indicated by the red bar for 24 hours and the dashed red bar for 48 hours) and MDA-MB-231 cells (represented by the green bar for 24 hours and the dashed green bar for 48 hours). Error bars denote the standard deviation (SD) based on three independent experiments ($n = 3$).

shown in Fig. 6, illustrating the percentage cell viability based on the treatment durations. The results indicated that RuPIP–Olap@ZIF-8-FA exhibited significant toxicity toward the cancer cells at lower concentrations after 48 hours, demonstrating higher toxicity to MCF-7 cells compared to MDA-MB-231 cells at the same time point. Additionally, the half-maximal inhibitory concentration (IC_{50}) values for each treatment were determined and are presented in Table 4. The IC_{50} value for MCF-7 cells at 48 hours was $11.38 \pm 0.64 \mu\text{g mL}^{-1}$, while for MDA-MB-231 cells, the value was $13.48 \pm 0.77 \mu\text{g mL}^{-1}$. Both these values were lower than that observed for HaCaT cells, in which RuPIP–Olap@ZIF-8-FA showed no toxicity.

In our previous study, we evaluated the cytotoxicity of the ZIF-8 carrier system on breast cancer cell lines and HaCaT normal cells. The results demonstrated that the cell viability for MDA-MB-231 and normal cells remained above 100%, whereas the system exhibited slight cytotoxicity against MCF-7 with an IC_{50} value of $75.86 \pm 5.02 \mu\text{g mL}^{-1}$ after 48 hours, indicating its potential for targeted anticancer therapy.⁵⁰

The effectiveness of drugs@nanoparticles against MCF-7 cells and MDA-MB-231 compared to HaCaT cells can be attributed to the acidic extracellular environment favouring the decomposition of the carrier and drug release. Notably, RuPIP–Olap@ZIF-8-FA displayed a lower IC_{50} value on MDA-MB-231 ($16.95 \pm 1.65 \mu\text{g mL}^{-1}$) compared to MCF-7 ($24.16 \pm 1.43 \mu\text{g mL}^{-1}$)

mL^{-1}) after 24 hours, indicating the enhanced targeting of MDA-MB-231 cells. The subsequent 48-h treatment showed decreased IC_{50} values for both cancer cell types due to the increased drug release from the nanoparticles, leading to greater growth inhibition. It is also worth mentioning that the reports in the literature indicate that the expression of folate receptor alpha (FR) is significantly upregulated in patients with triple-negative breast cancer, indicating its potential as both a diagnostic biomarker and therapeutic target.⁶⁶ These results may be affected by the biological mechanism such as the capacity of the target or drug metabolism pathway to remain active after exposure to a drug, and the drug sensitivity towards these cancer cells (drug resistance).⁶⁷

According to the results, it has been observed that the presence of pure ZIF-8 nanoparticles at low concentrations does not induce cytotoxic effects on MCF7, MDA-MB-231 and HaCaT cells. This indicates that cell growth can continue even in the presence of these nanoparticles, thereby facilitating sustained cell proliferation as the concentration of nanoparticles decreases.

Also, the cytotoxicity results showed that the folic-coated RuPIP–Olap@ZIF-8 can improve the anticancer properties of the combination drug system. With same concentration of drug ($\mu\text{g mL}^{-1}$), after 24 h the IC_{50} for MCF-7 cancer cells was about $27 \mu\text{g mL}^{-1}$, whilst this rate reduced to $24 \mu\text{g mL}^{-1}$ for coated

Table 4 Half maximal inhibitory concentration (IC_{50}) of RuPIP–Olap@ZIF-8-FA on MCF-7, MDA-MB231 and HaCaT normal cells for 24 and 48 hours

Treatment time (hours)	IC_{50} for MCF-7 ($\mu\text{g mL}^{-1}$)	IC_{50} for MDA-MB-231 ($\mu\text{g mL}^{-1}$)	IC_{50} for HaCaT ($\mu\text{g mL}^{-1}$)
24 h	24.16 ± 1.43	16.95 ± 1.65	>100
48 h	11.38 ± 0.64	13.48 ± 0.77	>100

ZIF-8, and after 48 h they were almost the same and the IC_{50} for MDA-MB-231 was reduced from 16 to $11 \mu\text{g mL}^{-1}$. The presence of folic ligand serves to direct and accumulate the drugs into the cell because breast cancer cells have an FA receptor on their surface, and thus when the nanoparticles are coated with FA, they are directed to bind with the surface of the cancer cells and penetrate them, consistent with the results reported by Handali *et al.* They found that the cytotoxicity of the target ligand FA-coated NPs was significantly increased compared to free drug and non-targeting NPs. Also, they suggested that FA-NPs may enter cancer cells by FA receptor-mediated endocytosis.⁶⁸ This difference in IC_{50} value between the NPs coated with FA and non-coated NPs is because the system without coating can only penetrate tumour tissue by passive targeting, while the coated system can bind with overexpressed FA receptors and easily facilitate its internalization. Consequently, the specific binding of folic acid to folate receptors enhanced the endocytosis of the nanoparticle in breast cancer cells due to their heightened proliferation rates and consequent overexpression of FAs on their cell surfaces. This overexpression makes folate receptors an optimal choice for targeted chemotherapeutic delivery

because they will foster increased drug uptake by folic acid-decorated DDSs through receptor-mediated endocytosis.⁶⁵

3.6 Apoptosis analysis of combined system and targeted combined system

The annexin-V/FITC assay was conducted to evaluate the effect of the drug encapsulated within ZIF-8 to induce apoptosis in cancer cells. To further investigate whether the mechanism of growth inhibition involves the induction of apoptosis and necrosis in cancerous cells, the apoptotic status of the cells was evaluated using flowcytometry analysis.

Breast cancer cells were treated with the control (untreated), pure ZIF-8, RuPIP-Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA NPs for 48 hours using the IC_{50} values. Previous research has showed that the co-drug treatment of free drugs RuPIP and Olap resulted in a high percentage of apoptotic cell death.⁶⁹ Accordingly, the rates of cell death were quantified in the same breast cancer cell lines using propidium iodide (PI) and annexin V staining. The percentage apoptotic cells was determined as the total of both late and early apoptotic cells. The results showed a significant increase in both early and late apoptotic cells in MCF-7 cells treated with the combination RuPIP-Olap@ZIF-8

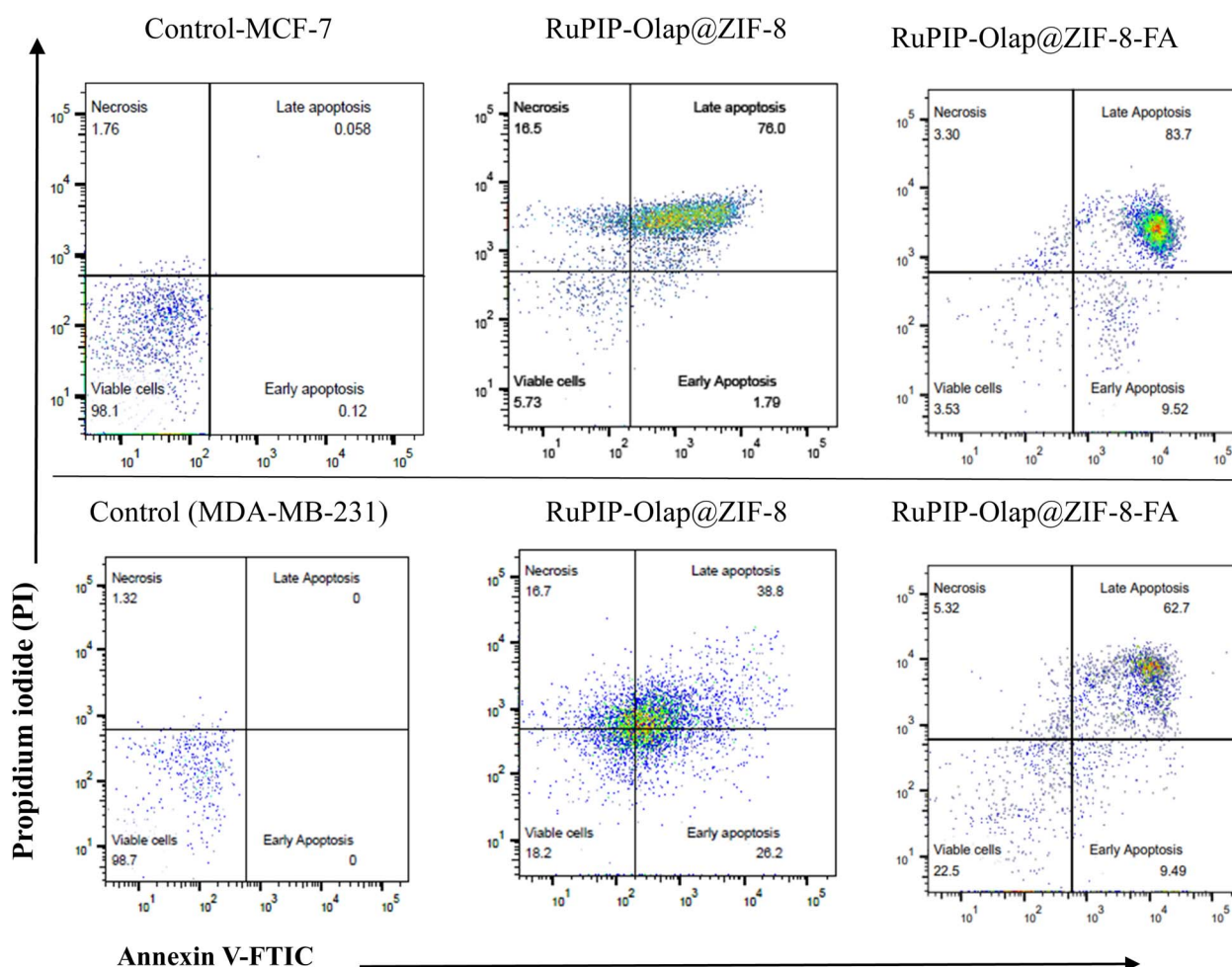


Fig. 7 Annexin V-FITC apoptosis assay of treated MCF-7 and MDA-MB-231 cells with coated combined targeting nanoparticle system after 48 hours.



nanoparticles, as shown in Fig. 7. A similar increase in apoptotic cells was also observed in the MDA-MB-231 cells, although to a lesser extent, correlating with the reduced activity of the treatment in this cell line. These results support the notion of controlled drug release from the nanoparticles upon their entry into cancer cells, leading to the observed cytotoxicity and resultant cell death primarily through apoptosis.

The cytotoxicity of the combined RuPIP and Olap encapsulated within ZIF-8 and coated with folic ligand has also been assessed against the MCF-7 and MDA-MB-231 cancer cells lines after 48 hours. Notably, the combination coated system therapy, RuPIP-Olap@ZIF-8-FA, involving RuPIP and Olap resulted in the significant escalation of both the early and late apoptosis rates, which for the nanoparticles coated with folic acid (FA) attained levels of 93.22% in MCF-7 cells and 72.19% in MDA-MB-231 cells compared to the combination system without the coating (77.76% and 65.0%), respectively. These results suggest that the FA coating may have significantly improved the cellular uptake and targeting of breast cancer cells, which characteristically overexpress folate receptors. This finding underscores that the integration of FA ligand moieties in the combinatorial nanoparticle system augments the pro-apoptotic efficacy of the chemotherapeutic agents against cancer cells.⁷⁰

To review the significance of these important findings, it is essential to compare the performance of the present RuPIP-Olap@ZIF-FA system with previously synthesized systems without the coated RuPIP-Olap@ZIF-8 although the combination studies demonstrated a good improvement in the physical and biological properties such as loading capacity and drug release of both drugs and high cytotoxicity and apoptosis rates on cancer cells were achieved. Physically coating the dual drug system with the targeting ligand FA resulted in an excellent dual-drug pH-responsive platform, especially in acidic environment. The current combined drug system, FA targeting ligand, and improved release kinetics collectively contribute to the superior cytotoxicity and reduced systemic toxicity observed. To clearly highlight these distinctions and the originality of our approach, a comparative summary of the main physical, and biological features is presented in Table 5 below.⁵⁰

ZIF-8 is known to undergo rapid degradation under acidic endosomal and lysosomal conditions, where protonation of its organic linker disrupts its framework, triggering the release of Zn^{2+} along with the encapsulated drugs.^{71,72} The released Zn^{2+} can participate in redox reactions that generate reactive ROS, inducing OH radicals through Fenton reactions,¹³ thereby

enhancing the cytotoxicity trends and complementing the therapeutic action of both drugs. These effects align with the cytotoxicity trends observed in our study and highlight the relevance of this system for the acidic, oxidative tumor microenvironment.

Mechanistically, drug@ZIF-8 is internalized through endocytosis, as supported by the SEM and XRD analyses. In acidic extracellular vesicles, ZIF-8 disassembles and releases the drug molecules, which then diffuse into the cytoplasm and enter the nucleus to exert their DNA-targeted effects. This intracellular behaviour is consistent with the previously reported pH-responsive disassembly and efficient delivery pathways of ZIF-8-based nanocarriers.⁷³

3.7 Acute toxicity effects of combination on zebrafish embryos

Zebrafish are valuable models for studying human metabolic disorders due to their similarities in morphology, genetics, and physiology. Additionally, they offer a cost-effective model for toxicity testing compared to traditional models such as mice and rats.⁷⁴ Zebrafish embryos, in particular, are highly sensitive to toxicity during their early developmental stages. This study conducted an acute *in vivo* toxicity experiment involving the exposure of zebrafish embryos to both single and combination agents delivered *via* ZIF-8. The toxicity levels were assessed by calculating the survival percentage at 96 hours post-incubation, a standard time point for examining the growth and development of zebrafish larvae.⁷⁵ The results indicated that pure ZIF-8, Olap@ZIF-8, RuPIP@ZIF-8, RuPIP-Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA exhibited concentration-dependent toxicity towards zebrafish embryos after 96 hours of incubation. Specifically, the survival rate of the embryos significantly decreased as the concentration of the nanotherapeutics increased from 15.60 to 1000 $\mu\text{g mL}^{-1}$, as illustrated in Fig. 8A. The highest concentration (1000 $\mu\text{g mL}^{-1}$) of functionalized RuPIP-Olap@ZIF-8-FA demonstrated a declining survival rate from the 24–120-h mark, as shown in Fig. 8B.

Furthermore, the nanotherapeutics also resulted in an increase in survivability. Notably, functionalized RuPIP-Olap@nZIF-8-FA resulted in a significantly higher survival rate ($P < 0.005$) compared to pure ZIF-8 and RuPIP-Olap@ZIF-8 without targeting agents at the 96-hour mark. Toxicity was quantitatively assessed by the measuring survival rates 96 hours post-incubation, providing essential insights into the safety profile of these nanotherapeutic agents and their potential

Table 5 Comparison of the main features between the dual-drug loaded system and FA-coated dual-drug loaded system.⁵⁰

Features	RuPIP-Olap@ZIF-8	RuPIP-Olap@ZIF-8-FA
Loading capacity	RuPIP 20.59% $\pm$ 1.38% Olap 10.77% $\pm$ 1.00%	A 1.4% reduction in RuPIP loading A 3.2% reduction in Olap loading
Release profile in pH 5.0 at 48 hours	RuPIP: 64% Olap: 90%	RuPIP: 80% Olap: 99%
IC ₅₀ of cancer cell: MCF-7	12.20 $\pm$ 2.58	11.38 $\pm$ 0.64
IC ₅₀ of cancer cell: MDA-MB-231	16.02 $\pm$ 0.84	13.48 $\pm$ 0.77
Apoptosis rates-MCF-7	77.79%	93.22%
Apoptosis rates-MDA-MB-231	65%	72.19%



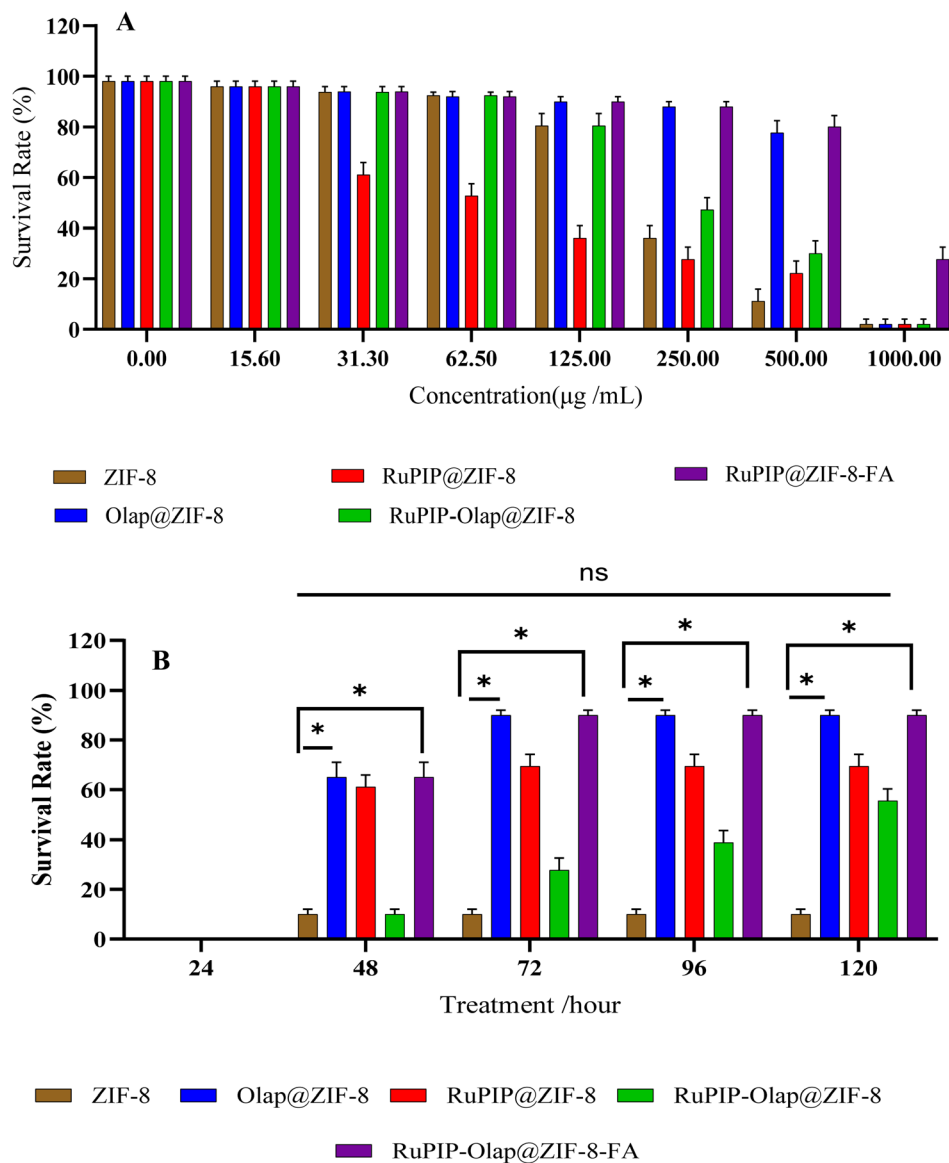


Fig. 8 Toxicity was evaluated after incubating zebrafish embryos with pure ZIF-8, Olap@ZIF-8, RuPIP@ZIF-8, RuPIP–Olap@ZIF-8, and RuPIP–Olap@ZIF-8-FA at (A) various concentrations for 96-hour and (B) the highest concentration ($125 \mu\text{g mL}^{-1}$) across incubation times ranging from 24 to 120 hours. Error bars represent the SD. Code: ns = non-significant and $*P < 0.005$. Error bars represent the standard deviation ($n = 3$).

therapeutic applications. After a 96-hour incubation with all the nanoparticles at concentrations of $500 \mu\text{g mL}^{-1}$, the malformations in the surviving zebrafish embryos were assessed, as shown in Fig. 9.

Scoliosis signs were particularly evident in the embryos treated with RuPIP@ZIF-8. At a concentration of $500 \mu\text{g mL}^{-1}$, aggregates of the nanocarrier were observed surrounding the porous chorion, likely contributing to a reduction in nanocarrier permeability. This study indicates that RuPIP–Olap@ZIF8-FA did not cause significant malformations, even at elevated concentrations, and did not present aggregation issues. Overall, low toxicity levels were noted across all four nanoparticle samples, with half maximal lethal concentration (LC_{50}) values exceeding the maximum concentration employed ($\text{LC}_{50} > 100 \mu\text{g mL}^{-1}$), as presented in Table 6.

The ZIF-8 carrier also exhibited concentration-dependent toxicity towards the zebrafish embryos following a 96-hour incubation period. The survival rates of the embryos significantly declined with an increase in the concentration of the nanotherapeutics, which ranged from 15.60 to $1000 \mu\text{g mL}^{-1}$. Among the drug nanoparticles, the highest concentration ($1000 \mu\text{g mL}^{-1}$) displayed a declining survival rate at the 48-hour mark, as depicted in Fig. 8A, likely due to drug release leading to diminishing drug availability. Despite demonstrating an increase in survivability after 48 hours, except for RuPIP@ZIF-8, which exhibited low survival rates at concentrations of $31.30 \mu\text{g mL}^{-1}$ and above, it was observed that the FA-coated dual system conferred a substantial survival advantage ($P < 0.005$), achieving a 90% survival rate compared to the combined RuPIP–Olap@ZIF-8, which only reached a 38.89% survival rate.



Fig. 9 Images depicting the development of zebrafish embryos and larvae taken at the following hours post fertilization (hpf): (a) 0 hpf, (b) 24 hpf, (c) 48 hpf, (d) 72 hpf, (e) 96 hpf and (f) 120 hpf. The embryos were treated with various compounds, including 1-ZIF-8, 2-Olap@ZIF-8, 3-RuPIP@ZIF-8, 4-RuPIP-Olap@ZIF-8, and 5-RuPIP-Olap@ZIF-8-FA, each at a concentration of $500 \mu\text{g mL}^{-1}$. The images were captured using an inverted microscope with magnifications of $100\times$ for panels (a–c) and $40\times$ for (d–f). *hpf = hours post fertilization.

In the zebrafish embryos, Olap@ZIF-8 with a single loaded drug exhibited mild toxicity, maintaining over 90% survival up to $500 \mu\text{g mL}^{-1}$ at the 96-hour point (96-hour LC_{50} value of $>789.53 \mu\text{g mL}^{-1}$). In contrast, after 96 hours of treatment with RuPIP@ZIF-8, the survival rate was 70% at a nanoparticle concentration of $31.3 \mu\text{g mL}^{-1}$, which declined to under 40% at

a concentration of $120 \mu\text{g mL}^{-1}$ of RuPIP@ZIF-8 (96 h LC_{50} of $22.6 \mu\text{g mL}^{-1}$, corresponding to $>31.25 \mu\text{g mL}^{-1}$).

It was noted that pure ZIF-8 exhibited minimal toxicity up to a concentration of $100 \mu\text{g mL}^{-1}$, with its toxicity increasing markedly beyond $100 \mu\text{g mL}^{-1}$. A significant difference ($P < 0.05$) in survival rates was observed when ZIF-8 was incubated

Table 6 Biological assessment of zebrafish

Nanoparticles	96 hpf LC_{50} ($\mu\text{g mL}^{-1}$)	96 LC_{50} ($\mu\text{g mL}^{-1}$)	Heart beat (min^{-1})	Delay hatching
ZIF-8	>100	182.64	$136.44 \pm 13.03 < 250 \mu\text{g mL}^{-1}$	Yes
Olap@ZIF-8	>100	789.53	$116.22 \pm 5.34 < 250 \mu\text{g mL}^{-1}$	No
RuPIP@ZIF-8	>100	22.66	$111.11 \pm 7.49 < 31.25 \mu\text{g mL}^{-1}$	No
RuPIP-Olap@ZIF-8	>100	197.92	$105.56 \pm 8.59 < 500 \mu\text{g mL}^{-1}$	Yes
RuPIP-Olap@ZIF-8-FA	>100	851.08	$160.00 \pm 4.90 < 500 \mu\text{g mL}^{-1}$	No

with embryos for 24 to 120 hours. Based on these findings, the lethal concentration (LC_{50}) for each nanotherapeutic was determined at the 120-hour lethal endpoint, with LC_{50} values exceeding $250 \mu\text{g mL}^{-1}$. This finding suggests that the tested concentrations were not detrimental to healthy zebrafish embryos. Additionally, malformations in the surviving zebrafish embryos were assessed after incubation with all treatments. The increased embryotoxicity of RuPIP@ZIF-8 at a high concentration of $50 \mu\text{g mL}^{-1}$ was possibly due to the enhanced lipophilicity of RuPIP, as drug absorption through the chorion layer is highly dependent on the lipophilicity of the drug.³⁶ Lipophilicity is commonly measured by $\log P$, where more lipophilic ruthenium complexes have shown higher cytotoxicity and cellular uptake, which may contribute to toxicity in zebrafish embryos. When the combination of both drugs, RuPIP-Olap@ZIF-8, was considered subtoxic, their concentration resulted in higher survival compared to the RuPIP single loaded drug, while the combination of RuPIP-Olap@ZIF-8 therapies tested also showed low toxicity, although at the highest concentration of combination $1000 \mu\text{g mL}^{-1}$. Furthermore, the folic acid-coated RuPIP-Olap@ZIF-8 at a concentration of $500 \mu\text{g mL}^{-1}$ exhibited an improved hatching rate compared to the uncoated RuPIP-Olap@ZIF-8, indicating the relatively safer profile for this specific drug-loaded ZIF-8.

The lethality rate of the zebrafish embryos at a concentration of $125 \mu\text{g mL}^{-1}$ was approximately 28% at 120 hours for the ZIF-8 carrier and RuPIP-Olap@ZIF-8. This rate increased to 86% at 120 hours for RuPIP@ZIF-8 and approximately 10% for Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA. Additionally, when the treatment concentration was reduced to half of $125 \mu\text{g mL}^{-1}$ (i.e., $62.5 \mu\text{g mL}^{-1}$), increasing the concentration of samples to $1000 \mu\text{g mL}^{-1}$ resulted in a high lethality rate (over 90%), with all the zebrafish embryos dying by 120 hours post-fertilization. At this concentration, all the nanoparticle samples completely prevented hatching. In contrast, treatment with Olap@ZIF-8 and RuPIP-Olap@ZIF-8-FA at concentrations below $250 \mu\text{g mL}^{-1}$ resulted in approximately 90% hatching at 72, 96 and 120 hpf, which was comparable to the control group treatment.

Hatching is a critical phase in the fish life cycle, significantly influencing the rate of embryo development. In the case of zebrafish, the typical hatching timeframe ranges from 48 to 72 hpf, depending on enzyme activity and embryonic movements.⁷⁶ This study investigated the hatching rate to assess the effects of incubation without functionalization using folate on zebrafish embryos. The results shown in Fig. 10B indicate that all the embryos successfully hatched following incubation with ZIF-8, Olap@ZIF-8, RuPIP@ZIF-8. However, hatching inhibition began at concentrations exceeding $500 \mu\text{g mL}^{-1}$ of RuPIP-Olap@ZIF-8-FA, resulting in only 90% of embryos hatching, with complete failure to hatch at higher concentrations. Similarly, both pure ZIF-8 and RuPIP-Olap@ZIF-8 exhibited hatching inhibition starting at $125 \mu\text{g mL}^{-1}$, with hatching rates of 10% and 55%, respectively. This inhibition is likely a result of the aggregation of the nanocarriers around the chorion, which may interfere with its elasticity and hinder the release of the metalloprotease enzymes that are crucial for weakening the chorion and facilitating embryo release.⁷⁷ Conversely, hatching

was affected by treatment with RuPIP@ZIF-8 and Olap@ZIF-8, with complete prevention of hatching observed at concentrations of $1000 \mu\text{g mL}^{-1}$ for both treatments, leading to hatching rates of approximately 60% and 45% at $500 \mu\text{g mL}^{-1}$, respectively. Hatching success serves as a sensitive indicator in zebrafish embryo toxicity assessments, where delayed hatching may indicate impaired embryo development, while failed hatching often results in fatal outcomes.⁷⁸ Collectively, our findings suggest that olaparib loaded in ZIF-8 may exhibit lower toxicity compared to RuPIP when administered singly.

The mortality rate of zebrafish is markedly influenced by the type and concentration of anticancer drug-loaded MOFs. Certain MOFs and drug combinations exhibit notable toxicity, whereas others, particularly those formulated for targeted delivery, present encouraging safety profiles with minimal adverse effects.^{79,80} Nevertheless, among the nanoparticle group, the highest mortality rate is associated with RuPIP@ZIF-8, then pure the ZIF-8 carrier, while Olap@ZIF-8 and a combination drug coated with FA do not significantly elevate the mortality compared to RuPIP-Olap@ZIF-8, which demonstrates slightly higher mortality than the targeted system, as shown in Fig. 10A. Zebrafish are frequently employed to assess the

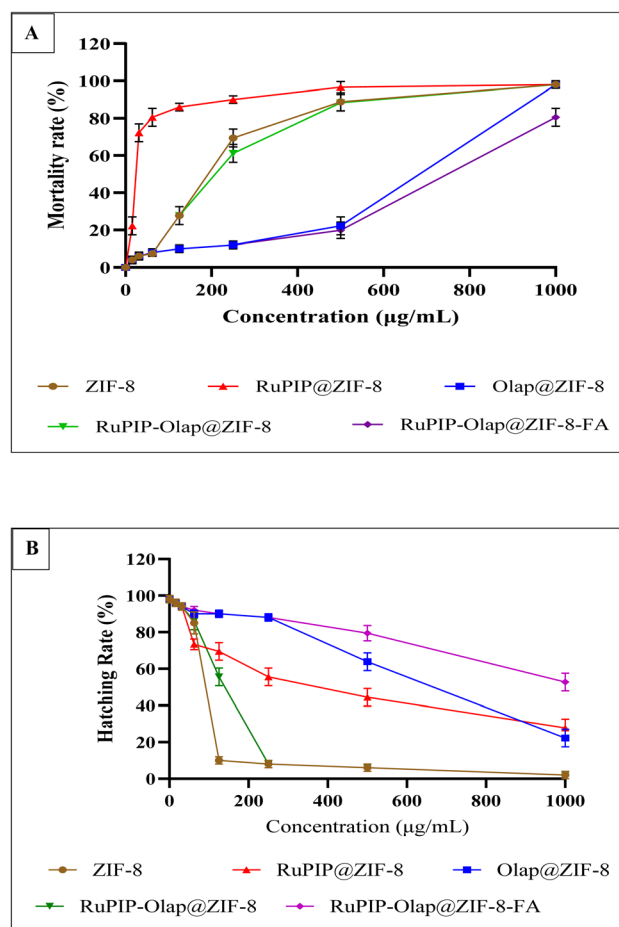


Fig. 10 (A) Embryo mortality rate and (B) hatching rate when treated with pure ZIF-8 and drugs encapsulated within ZIF-8 in individual and combination therapy at different concentrations observed at 96 h. Error bars represent the standard deviation ($n = 3$).



cardiotoxicity of various drugs, including anticancer agents, due to the observed cardio-toxic effects with these agents.⁸¹ Consequently, it is conceivable that subjecting these drugs to loading within MOFs may either ameliorate or exacerbate these effects depending on the release profile and bioavailability of the drug. The use of MOFs potentially alters the pharmacokinetics and biodistribution of the drugs, consequently impacting the magnitude of cardiotoxicity. Thus, the modulation of drug release and distribution has the potential to influence the severity of cardiotoxic effects.

Higher concentrations ($>100 \mu\text{g mL}^{-1}$) of ZIF-8 were found to influence the heart development and hatching time in the zebrafish embryos, indicating its potential impact on cardiac function, as shown in Fig. S7(A–E). When tested on zebrafish, the anticancer drug RuPIP@ZIF-8 displayed a reduction in the force of heart contractions at concentrations exceeding $62.5 \mu\text{g mL}^{-1}$ ($p < 0.001$), while Olap@ZIF-8 affected the heart rhythm at concentrations greater than $250 \mu\text{g mL}^{-1}$ ($p < 0.001$). These findings suggest that anticancer drugs encapsulated by ZIF-8 may elicit complex effects on heart function, encompassing both positive chronotropic (increased heart rate) and negative inotropic (decreased force of contraction) effects.

Next, the combination system showed less impact on cardiac rate than the individual system of RuPIP@ZIF-8 at concentrations more than $250 \mu\text{g mL}^{-1}$ ($p < 0.001$). Also, the combination system coated with FA exhibiting less effect on the cardiac rate gave a good indication about the effect of coating for reducing the toxicity effect of dual system, resulting in better survivability by the coated nanoparticle system towards healthy zebra embryos. In agreement with *in vitro* cell toxicity study, the coated system less induced toxicity toward normal HaCaT cells compared to MCF-7 and MDA-MB-231 cells. Next, the lethal concentration to kill 50% of embryos (LC_{50}) for each sample was calculated at its leather point of 96 h. It was found that Olap@ZIF-8 and the coated nanoparticle system did not kill 50% of embryos with LC_{50} than $500 \mu\text{g mL}^{-1}$. This finding is agreement with Ma *et al.*, who found that folic acid protected against arsenic-mediated embryo toxicity, thus increasing the hatching and survival rates and decreasing the malformation rate and abnormal cardiac rate in zebrafish embryos exposed to arsenite.⁸²

4 Conclusion

Targeted nanoparticle delivery systems have advanced considerably in recent years, improving the transport of therapeutic and diagnostic agents to tumour sites. Also, a variety of innovative strategies have been implemented to overcome their limitations such as non-specific distribution and inadequate targeting precision. This study focuses on a folate receptor-targeting folic acid-coated system of RuPIP–Olap@ZIF-8 utilizing *in vivo* studies.

During the *in vivo* studies, this system demonstrated notable potential as a targeted drug delivery mechanism for cancer treatment, effectively facilitating the controlled release of ruthenium polypyridyl (RuPIP) and olaparib (Olap) within the cancer microenvironment, while reducing their toxicity levels.

The use of a folic acid (FA) coating generally enhances the therapeutic targeting and delivery efficiency. However, it is essential to intensify the exploration of ZIF-8 nanocarriers as compatible carriers.

The FA-coating (physical absorption on ZIF-8 surface) have demonstrated considerable potential by significantly increasing the survival rates of zebrafish embryos and reducing *in vivo* toxicity to healthy tissues in comparison to non-targeted nanocarriers. Given that folic acid (FA) serves as a high-affinity ligand for folate receptors, which are overexpressed on the surface of many cancer cell types, especially, breast cancer, further optimization and quantification of FA coatings are critical to maximize selective tumor targeting. Additionally, assessing receptor-mediated endocytosis using FA-ligand or folate-deficient cell models would provide mechanistic confirmation of the targeting advantage conferred by FA modification.

Furthermore, these delivery platforms have persistently shown improved inhibition of cell proliferation, promoted mitochondria-mediated apoptosis, mitigated drug side effects, and prolonged overall survival. Additionally, this system effectively facilitated the controlled release of ruthenium polypyridyl (RuPIP) and olaparib (Olap) within the cancer microenvironment, achieving significant inhibition rates exceeding 50% in MCF-7 and MDA-MB-231 breast cancer cell lines, indicating their high toxicity towards cancer cells. RuPIP–Olap@ZIF-8-FA shows considerable promise as a targeted nanocarrier for cancer therapy, potentially offering a safer and more effective alternative to traditional chemotherapy regimens.

Future studies should also assess how FA coating influences the biodistribution process, circulation time, and clearance pathways *in vivo*, particularly in comparison to non-targeted RuPIP–Olap@ZIF-8 carriers. Integrating FA with other targeting ligands or stimuli-responsive strategies such as pH-triggered or redox-triggered release may further enhance the precision and therapeutic index of the platform. Furthermore, expanding the toxicity assessments, long-term stability analyses, and pharmacokinetic profiling will be crucial to validate the safety and efficacy of FA-coated ZIF-8 nanocarriers. Collectively, these advancements will accelerate the development of RuPIP–Olap@ZIF-8-FA as a next-generation, actively targeting nanotherapeutic with improved tumor specificity, reduced cytotoxicity, and enhanced combined drug delivery performance.

Ethical statement

Ethical approval, the zebrafish (*Danio rerio* F. Hamilton, 1822) brood stocks in Danio Assay Laboratories Sdn. Bhd. facilities are performed under permission of Institutional Animal Care and Use Committee (IACUC), Universiti Putra Malaysia (UPM/IACUC/AUP-R044/2022).

Author contributions

Noor S. Sadeq: investigation, designed the experiments and writing – original draft; Syahida Ahmad: zebrafish data investigation, Mas Jaffri Masardudin: investigation, data curation; Mohd Basyaruddin Abdul Rahman: investigation, data



curation; Suet Lin Chia: investigation; data curation; Haslina Ahmad: supervision; conceptualization; review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: TEM images of all nanoparticle systems, figures showing kinetic models for RuPIP-Olap@ZIF-8-FA, figures showing the effect of nanoparticle concentration on zebrafish heartbeat, experimental section containing details of the sample preparation and an explanation of the protocol for the procedure, and figures showing TGA-DTA results. See DOI: <https://doi.org/10.1039/d5ra07756g>.

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