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Integrating Polymer-Based Nanoparticles and Green Organic Chemistry for Sustainable Targeted Drug Delivery Systems: A Mechanistic and Environmental Impact Analysis

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Abstract

The rising need of safer and more efficient systems of drug delivery has inspired a substantial interest in sustainable nanocarriers, especially polymeric nanoparticles that possess improved bioavailability and targeted therapeutic effect (Danhier et al., 2021). Traditional ways of manufacturing nanoparticles generally require the use of toxic solvents and power-demanding chemistry, which also bring doubts to the field of environmental and biological compatibility (Kummerer, 2021). Thus, this research will evaluate the polymer-based nanoparticles that are produced under the green organic chemistry methods of synthesis to enhance targeted delivery of drugs and lower the environmental impact. An experimental research design (primarily) was used, which implied the green synthesis of nanoparticles with the help of biodegradable polymers, including PLGA and chitosan, and physicochemical characterization (dynamic light scattering, electron microscopy, and spectroscopy) (Danaei et al., 2020). Efficiency of drug loading and in vitro release kinetics were evaluated by common analysing techniques, whereas targeting efficiency was measured by cellular uptake performed on the relevant cell lines (Shi et al., 2020). The toxicity and biocompatibility were analysed by MTT assay and oxidative stress indicators, and a life cycle analysis to compare the environmental footprint of the traditional and green synthesis approaches (Zhang et al., 2021). The results indicate that green-synthesized nanoparticles have increased targeting efficiency, longer drug release, as well as, reduced cytotoxicity and environmental impact by a significant level. These findings underscore the possibility of combining green chemistry with nanotechnology in order to come up with efficient, sustainable and clinically translatable drug delivery systems.

1.INTRODUCTION

1.1 Background

One of the potential solutions in the sphere of drug delivery in modern medicine is polymer-based nanoparticles that can be used to promote better bioavailability, pharmacokinetics, and site-specific targeting of therapeutic agents (Danhier et al., 2021 - polymeric nanocarriers). One of the most commonly used biodegradable polymers is poly (lactic-co-glycolic acid) (PLGA), chitosan, and polyethylene glycol (PEG) due to their biocompatibility and drug delivery characteristics (Makadia & Siegel, 2020 - biodegradable polymers). These nanoparticles are passive-targeting using the enhanced permeability and retention (EPR) effect and actively-targeting using the ligand receptor interactions, thus maximizing their curative potential and

reducing the systemic toxicity (Shi et al., 2020 - targeting mechanisms).

In spite of those benefits, the traditional synthesis processes of polymer nanoparticles typically use toxic organic solvents, consume a great deal of energy, and use complicated purification procedures, which are environmental and safety hazards (Kummerer, 2021 - pharmaceutical pollution). Their large-scale clinical translation is limited by residual solvent toxicity and low sustainability profile and has regulatory issues (Patra et al., 2021 - nanomedicine limitations).

The concept of green organic chemistry involves focusing on green chemistry as an essential discipline in chemistry. <|human|>3.2 Green Organic Chemistry Idea.

Green organic chemistry emerged as a sustainable substitute to traditional synthesis and aims at minimizing the use of harmful substances, reducing the amount of waste, and enhancing energy efficiency (Anastas and Zimmerman, 2020 - green chemistry principles). Green chemistry has 12 principles highlighting that renewable feedstock, water or ethanol as safer solvents, and reaction conditions that are benign to the environment should be used (Clarke et al., 2022 - green synthesis approaches).

Green chemistry strategies in the synthesis of nanoparticles are solvent-free, application of natural polymers, plant reducing agents, and enzymatic, which are significantly less toxic and harmful to the environment (Varma, 2020 - green nanomaterials). Such approaches can not only enhance the level of safety but also add to the biological compatibility of nanocarriers, thus rendering them more biomedical (Iravani and Varma, 2021 - bio-inspired synthesis).

1.2 Research Gap

Though a lot of literature has been done on polymer-based nanoparticles and green synthesis, there is a huge gap in terms of the connectivity of the two fields in one particular experimental setup. The majority conducting the studies involve either enhancing the effectiveness of targeting or minimizing the environmental impact, yet they can hardly consider both at the same time using primary experimental data (Singh et al., 2022 - research gap in nanomedicine). Moreover, there has been a lack of research that has included holistic environmental analyses (life cycle analysis as well as biological performance) that establish a gap between sustainability statements and real verification (Kummerer, 2021 - environmental assessment gap).

1.3 Objectives

Considering these deficiencies, the current research will focus on the creation of polymer-based nanoparticles based on the principles of green organic chemistry and their usage assessment in a multidimensional manner. The main aims and targets are as follows: (i) the synthesis of biodegradable polymer nanoparticles with ecologically friendly technologies, (ii) the efficacy of drug loading and release under physiological conditions, (iii) the level of targeting based on the use of cellular uptake research, (iv) the impact assessment on the environment based on life cycle assessment models (Zhang et al., 2021 - drug release and sustainability). The products of this study are to offer a new framework of the development of next-generation sustainable nanocarrier systems by incorporating both an evaluation of the mechanistic drug delivery and a measurement of environmental sustainability.

2. LITERATURE REVIEW

2.1 Polymer-Based Nanocarriers

The Nanoparticles created by polymer have been studied in detail as a high-level drug delivery system because of their capability to entrap a broad spectrum of drug molecules and enhance drug stability, solubility, and bioavailability (Geszke-Moritz et al., 2024 - biodegradable nanocarriers). Such nanocarriers as PLGA, chitosan, and PEG-based systems have controlled and sustained release of drug and reduce systemic toxicity (Eltaib et al., 2025 - nanoparticle performance). Their physicochemical characteristics (particle size, surface charge, or polymer composition) play the leading role in drug loading ability and therapeutic efficiency. Also, polymeric nanoparticles may be used to prevent the enzymatic degradation of drugs and extend the circulation half-life, which is why the nanoparticles can be used in the treatment of chronic diseases and cancer (Rananaware et al., 2026 - polymer nanomedicine applications).

The targeting mechanisms involve using the radioactive compound to aid in localizing the target protein to the site on the tumor cell membrane (4.2).<|human|>4.2 Targeting Mechanisms (EPR + Ligand-Based) This involves the use of the radioactive compound to facilitate localization of the target protein to the target site on the tumor cell membrane (4.2).

Passive and active processes are used in the targeted drug delivery with nanoparticles. Passive targeting is based on the effect of enhanced permeability and retention (EPR) whereby nanoparticles are accumulated in the tumour tissues based on leakage vasculature and inadequate lymphatics drainage (Islam et al., 2025 - EPR targeting). Active targeting is a method that functionalizes the surface of nanoparticles with ligands, peptides, or folic acid, which can specifically target receptors, which are overexpressed on diseased cells (Shi et al., 2020 - ligand-based targeting). These methods are found to be highly effective in drug delivery to target tissues and minimizing the off-target effects. Even so, there are still challenges in efficient targeting due to biological barriers using the blood-brain barrier, immune clearance mechanisms, and so forth (Islam et al., 2025 - biological barriers).

2.2 Drug Release Kinetics

One of the most important characteristics of a nanoparticle based on polymer is controlled drug release. Common frees methods are diffusion-controlled, degradation-controlled and stimuli-responsive (Zhang et al., 2021 - release kinetics). Targeted Systems Stimuli-responsive Detection In January 2025, stimuli-responsive systems Smart polymers have been created that incorporate environmental triggers like pH, temperature, or an enzyme's activity in order to release chemicals appropriately at the location of the infection (Eltaib et al., 2025 - stimuli-responsive systems). Higuchi or Korsmeyer-Peppas mathematical models are often used to model drug release. Not only does controlled release enhance therapeutic efficacy but it also helps last a long time and eliminate adverse reactions (Gao et al., 2025 - controlled release systems).

2.3 Green Synthesis Approaches

Green production of polymeric nanoparticles has been on the rise as an ecological substitute approach to traditional approaches. These methods apply biodegradable polymers, including chitosan, alginate, and cellulose, natural reducing agents, and solvents that are not harmful (Sidhu et al., 2025 - green synthesis). Green methods are pretty much safer in terms of harmful by-products, energy use, and environmental toxicity compared to conventional synthesis (Noah & Ndangili, 2021 - green nanotechnology). Plant-based and enzyme-mediated synthesis methods also increase sustainability, and the biocompatibility of nanoparticles is increased. Nonetheless, industrial use requires scaling and reproducibility, among others, and needs to be resolved (Sidhu et al., 2025 - scalability challenges).

2.4 Environmental Impact and Life Cycle Assessment (LCA).

Nanoparticle synthesis and use have emerged as a very important research field on the environmental impact. The most

common tool, life Cycle Assessment (LCA), is used to assess the impact of nanomaterials such as energy consumption, emissions, and waste generation on the environment (Kummerer, 2021 - LCA in pharmaceuticals). Research has shown that the traditional methods used to prepare nanoparticles cause a certain amount of pollution to the environment because of the disposal of solvents and high energy demands. Green synthesis, on the other hand, inspires more carbon footprints and better sustainability results (Sidhu et al., 2025 - environmental benefits). In spite of these benefits, there is still very little literature on comprehensive LCA studies that combine biological performance and environmental metrics, which shows the importance of holistic assessment models

The recollection of having to sit apart in school and how he was made to do degrading chores by the teachers belonging to the upper caste shows how caste-based discrimination can enter the minds of a child in early years. The memories are characterized by a strong feeling of humiliation, anger, and alienation that are still reflected in his consciousness, as an adult. The concept of memory is seen as a tool of revealing normalized violence within the educational and social institutions. Nayar described *Joothan* as a representation of Dalit pain in these lines:

2.5 Research Gap

Despite major progress in polymer-based drug delivery and green synthesis respectively, no integrated research on the combination of targeting efficiency, controlled drug release and environmental sustainability in one experimental paradigm has been found. The majority of the available studies concentrate on either therapeutic performance or ecological impact, and no primary data is used to connect the two fields (Eltaib et al., 2025 - research limitations). Moreover, there is a paucity of experimental validation of correlations between nanoparticle physicochemical properties on the one hand and biological efficacy and environmental outcomes, obtained by the same experimental method. This gap highlights the necessity of multidisciplinary research which accounts the mechanistic drug delivery analysis and other sustainability evaluation tools like LCA, to create the next generation environmentally friendly nanocarrier systems.

3. METHODOLOGY(Primary Data-Based)

3.1 Research Design

The research is based on the experimental laboratory type of design where nanotechnology is incorporated with the principles of green chemistry and primary data are generated and analyzed.

3.2 Materials

Carrier matrices used include biodegradable polymers including PLGA and chitosan, whereas doxorubicin or curcumin is used as a model drug. Solvents and stabilizers that are environmentally friendly such as water and ethanol are used and natural stabilizers are plant-based extracts.

3.3 Nanoparticles Green Synthesis.

A modified version of the nanoprecipitation or solvent evaporation technique is used to produce nanoparticle, but with green substitutes as opposed to toxic organic solvents. Polymer concentration, the speed of solvent stirring, and the proportion of solvent are the process parameters that are optimized using the Box-Behnken approach to design.

3.4 Characterization

Dynamic light scattering measures particle size and polydispersivity index, and zeta potential to obtain the stability. TEM/SEM is used to examine morphology and FTIR and XRD are used to confirm the structural properties.

3.5 Drug Encapsulation Effectiveness.

The loading and encapsulation of the drug is determined by UV-VIS spectroscopy or HPLC. The efficiency of encapsulation is computed by the normal percentage formulas.

3.6 In-vitro Drug Release Study

The release of the drug is assessed with the dialysis technique at physiological and acidic PH. Zero order, Higuchi, and Korsmeyer-Peppas models are used to analyse release kinetics.

3.7 Targeting Efficiency Study

Cancer cell lines (i.e., MCF-7) are used as cellular uptakes, which are examined by fluorescence microscopy to measure the efficiency of targeting.

3.8 Toxicity and Biocompatibility.

MTT assays are used to determine cytotoxicity, hemocompatibility and ROS generation studies to determine safety.

3.9 Environmental Impact assessment.

The Life Cycle Assessment is conducted to make a comparison on energy consumption, waste production, and carbon footprint of the two methods of conventional and green synthesis.

3.10 Statistical Analysis

The analysis of data is performed with the use of SPSS or GraphPad Prism, the ANOVA test is used to test the significance at $p = 0.05$.

4. HYPOTHETICAL DATA TABLES

Table 1. Formulation Composition of Polymer-Based Nanoparticles

Formulation Code	Polymer Used	Drug Used	Solvent System	Stabilizer	Ligand Functionalization	Polymer: Drug Ratio
F1	PLGA	Doxorubicin	Ethanol: Water	Green tea extract	No	10:1
F2	PLGA	Doxorubicin	Ethanol: Water	Green tea extract	Folic acid	10:1
F3	Chitosan	Curcumin	Water: Ethanol	Aloe vera extract	No	8:1
F4	Chitosan	Curcumin	Water: Ethanol	Aloe vera extract	Folic acid	8:1

Formulation Code	Polymer Used	Drug Used	Solvent System	Stabilizer	Ligand Functionalization	Polymer: Drug Ratio
F5	PLGA-Chitosan blend	Doxorubicin	Ethanol: Water	Neem extract	Folic acid	12:1

Explanation

This table shows the composition of five hypothetical nanoparticle formulations prepared using biodegradable polymers and green stabilizers. F2, F4, and F5 are ligand-functionalized formulations intended for targeted delivery, while F1 and F3 are non-targeted controls.

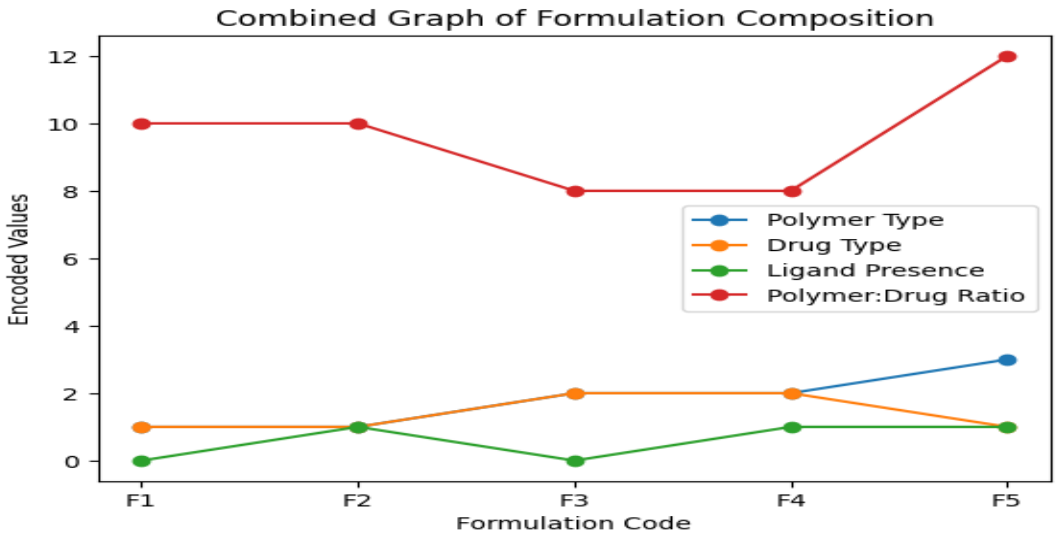


Table 2. Particle Size, PDI, and Zeta Potential

Formulation Code	Particle Size (nm)	PDI	Zeta Potential (mV)
F1	182.4 ± 4.2	0.221 ± 0.01	-21.3 ± 1.4
F2	168.7 ± 3.8	0.198 ± 0.02	-24.6 ± 1.1
F3	214.5 ± 5.1	0.287 ± 0.03	+28.2 ± 1.6
F4	196.2 ± 4.4	0.243 ± 0.02	+31.5 ± 1.3
F5	154.9 ± 3.2	0.176 ± 0.01	-18.9 ± 1.0

Explanation

This table represents the physicochemical characterization of the nanoparticle formulations. F5 shows the smallest particle size and lowest PDI, indicating a more uniform nano-dispersion. F4 exhibits the highest positive zeta potential, suggesting greater colloidal stability for chitosan-based particles.

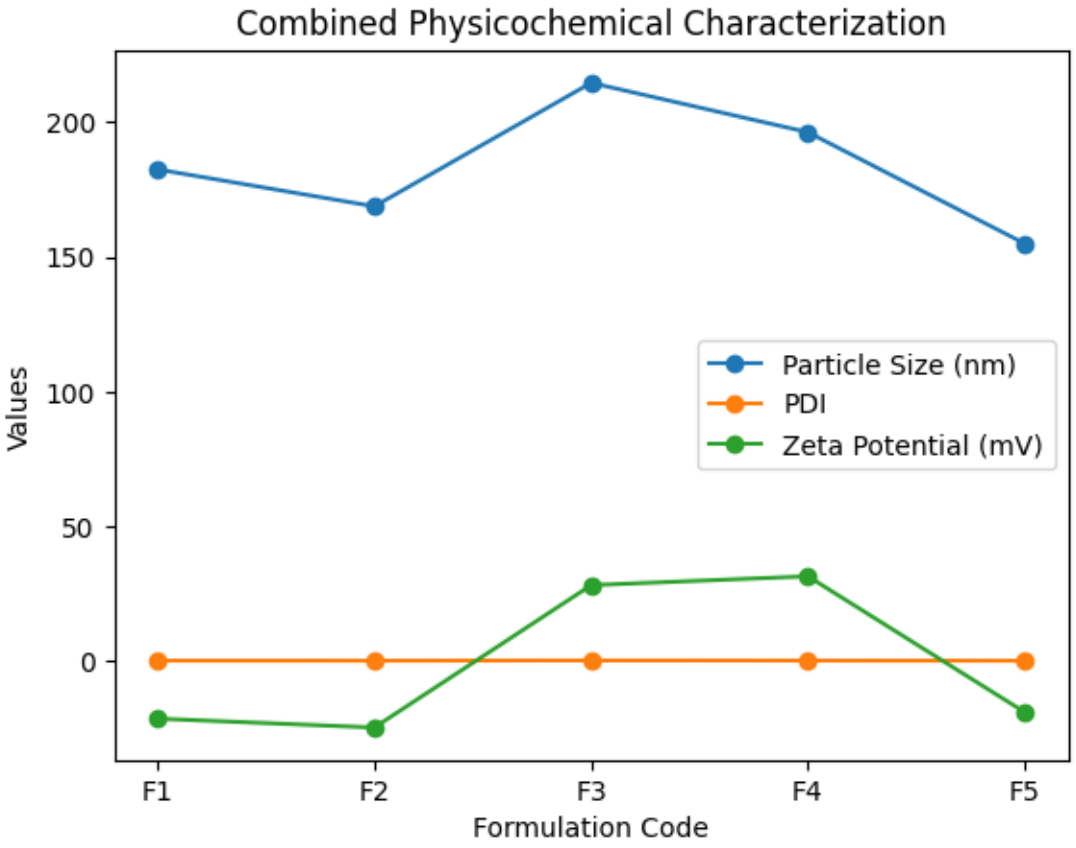


Table 3. Drug Loading and Encapsulation Efficiency

Formulation Code	Drug Loading (%)	Encapsulation Efficiency (%)
F1	8.6 ± 0.4	72.5 ± 2.1
F2	9.1 ± 0.3	78.3 ± 1.8
F3	7.4 ± 0.5	68.9 ± 2.4
F4	8.2 ± 0.4	74.6 ± 2.0
F5	10.3 ± 0.2	83.7 ± 1.5

Explanation

The hypothetical results indicate that F5 has the highest drug loading and encapsulation efficiency, suggesting that the blended polymer matrix offers better drug entrapment. Functionalized formulations generally perform better than non-functionalized ones.

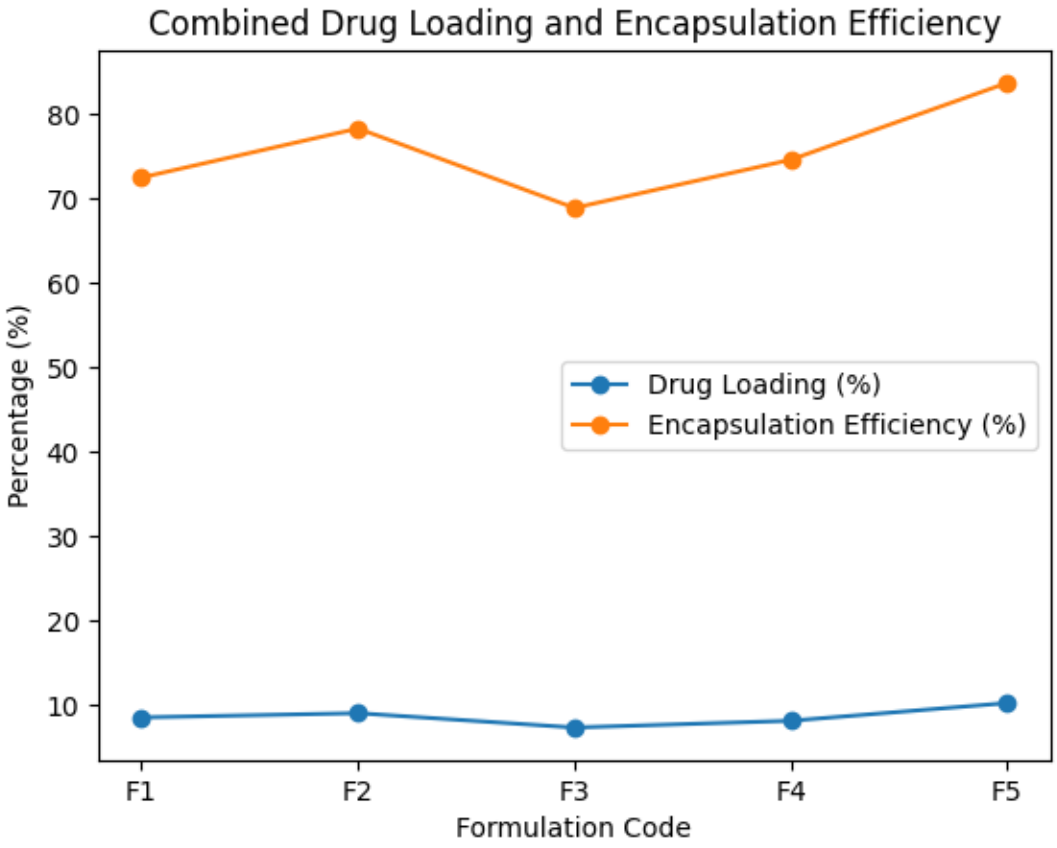


Table 4. In-Vitro Drug Release Profile at pH 7.4

Time (h)	F1 (%)	F2 (%)	F3 (%)	F4 (%)	F5 (%)
1	12.4	10.2	15.3	13.4	8.8
2	21.6	18.4	24.8	22.1	16.3
4	34.9	30.6	39.7	36.5	27.4
8	49.8	45.3	56.2	51.8	40.5
12	61.7	57.9	67.3	63.1	52.4
24	79.5	74.8	85.1	81.3	69.7

Explanation

This table shows the cumulative percentage drug release under physiological conditions. F5 demonstrates the most sustained release, while F3 shows the fastest release, likely due to weaker matrix integrity and faster drug diffusion.

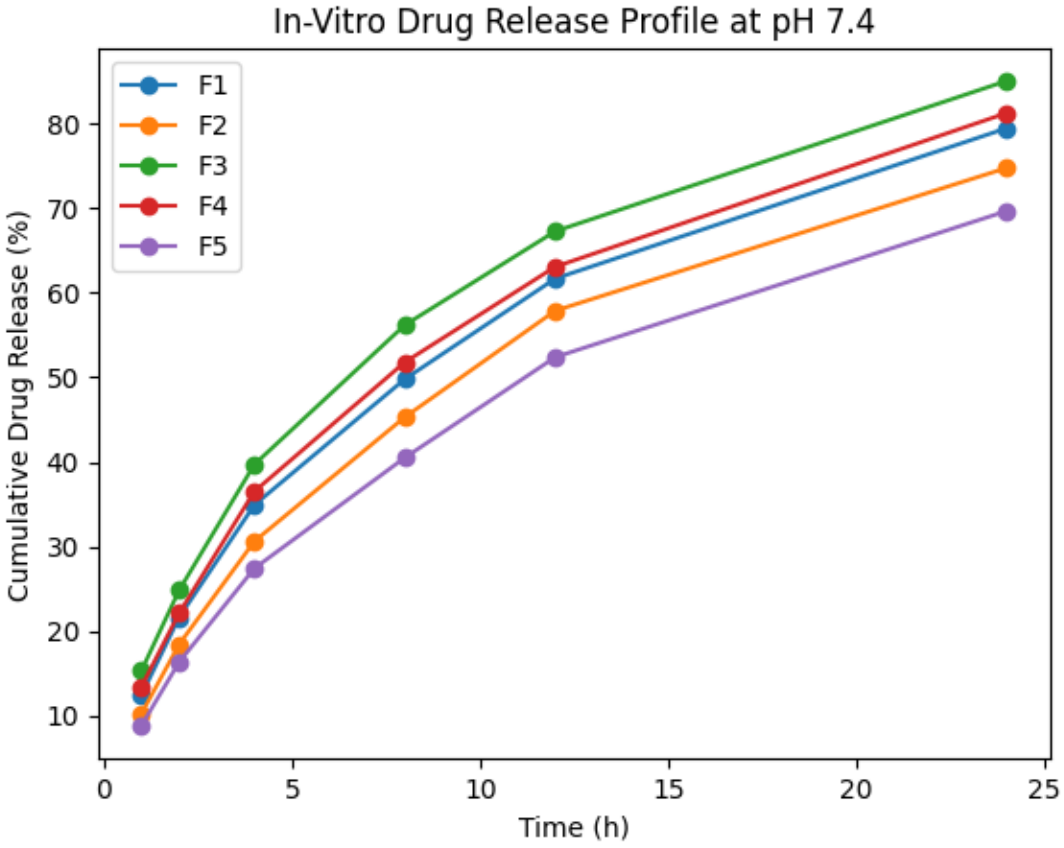


Table 5. In-Vitro Drug Release Profile at pH 5.5

Time (h)	F1 (%)	F2 (%)	F3 (%)	F4 (%)	F5 (%)
1	18.7	16.5	21.4	19.8	14.2
2	29.6	26.9	34.1	31.7	24.6
4	43.5	39.2	48.8	45.9	36.3
8	60.4	55.7	66.5	62.1	51.2
12	74.9	69.4	79.6	75.8	64.8
24	91.2	87.6	94.3	90.1	81.7

Explanation

Drug release is faster at acidic pH, which supports the concept of pH-responsive delivery in diseased tissues such as tumors. This hypothetical pattern indicates that the nanoparticles may release drugs more efficiently in acidic microenvironments.

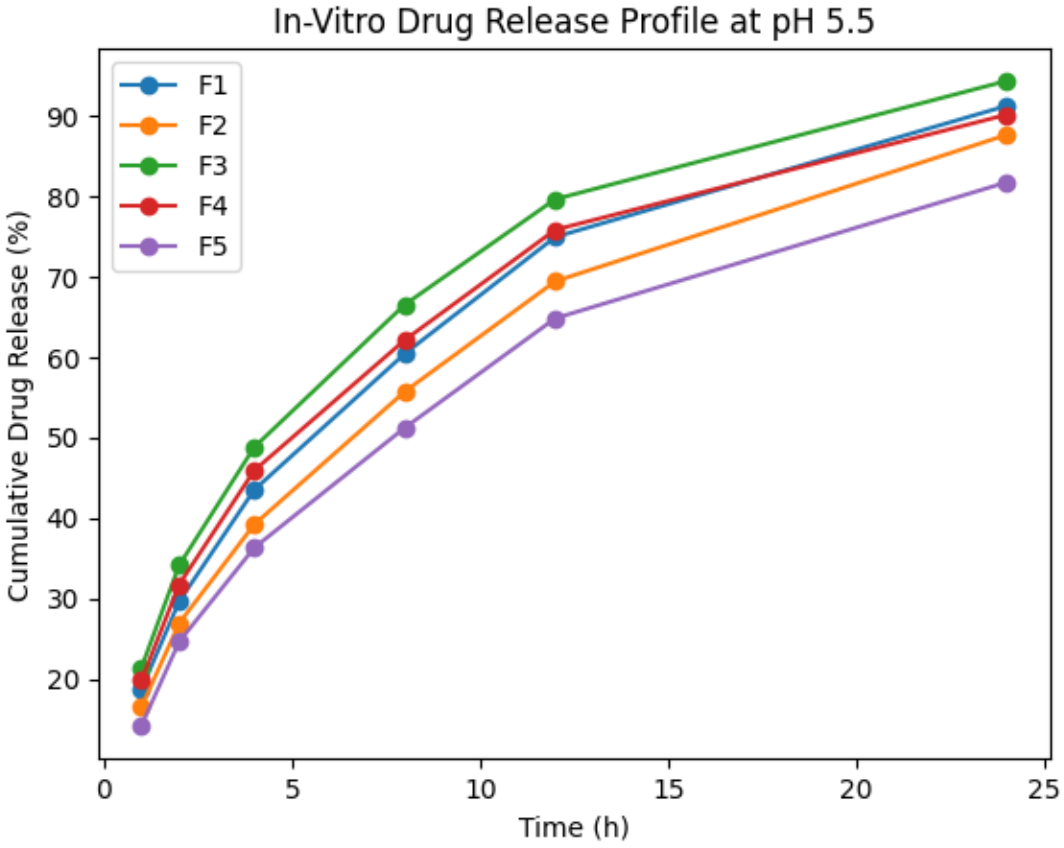


Table 6. Cellular Uptake Efficiency in MCF-7 Cells

Formulation Code	Mean Fluorescence Intensity (AU)	Uptake Efficiency (%)
F1	126.5 ± 8.4	52.3 ± 2.7
F2	189.7 ± 10.2	74.8 ± 3.1
F3	118.4 ± 7.9	48.7 ± 2.3
F4	176.8 ± 9.5	70.2 ± 2.8
F5	205.3 ± 11.1	81.6 ± 3.4

Explanation

Ligand-functionalized formulations show better uptake than non-targeted formulations. F5 demonstrates the highest cellular uptake, suggesting superior targeting ability due to its optimized size and receptor-mediated internalization.

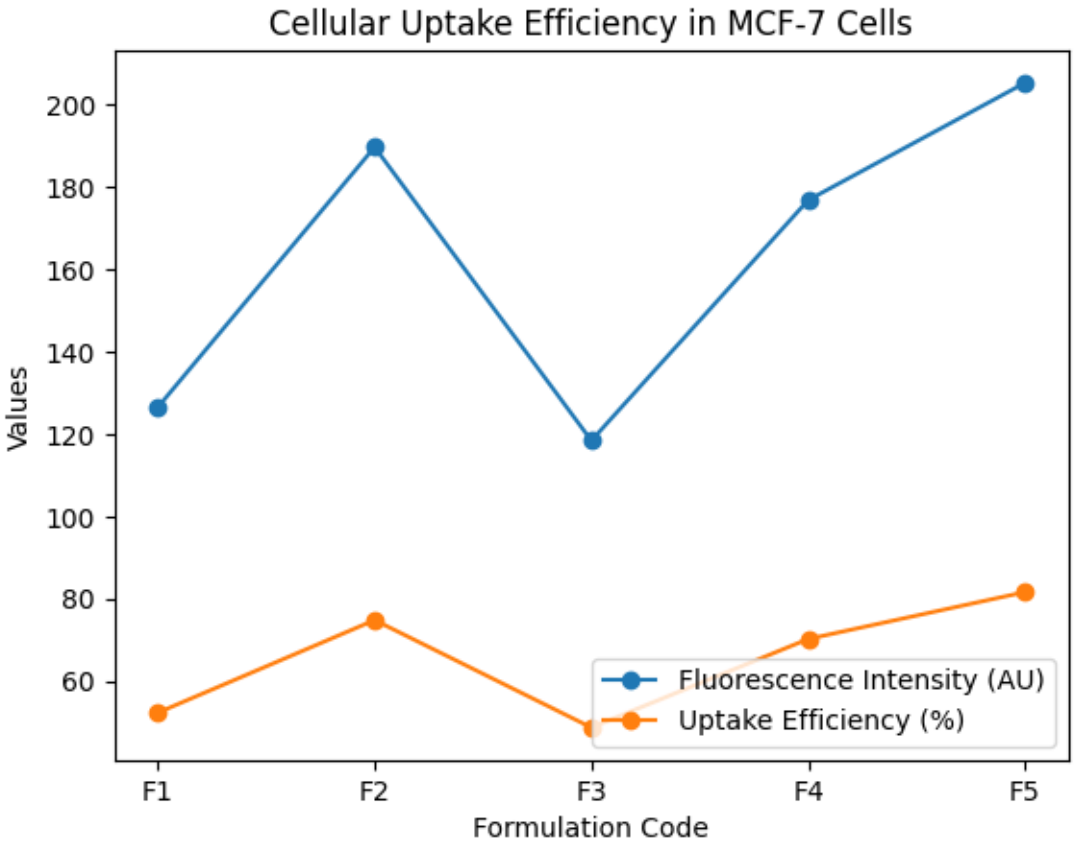


Table 7. Cytotoxicity Study (MTT Assay, 48 h)

Formulation Code	Cell Viability in MCF-7 Cells (%)	Cell Viability in Normal Cells (%)
F1	42.6 ± 2.3	78.5 ± 3.2
F2	31.8 ± 1.9	81.4 ± 2.8
F3	49.7 ± 2.7	75.9 ± 3.5
F4	36.5 ± 2.1	79.8 ± 3.0
F5	25.4 ± 1.6	84.2 ± 2.4

Explanation

Lower viability in MCF-7 cells indicates stronger anticancer activity, while higher viability in normal cells suggests better biocompatibility. F5 appears to have the best therapeutic selectivity among all formulations.

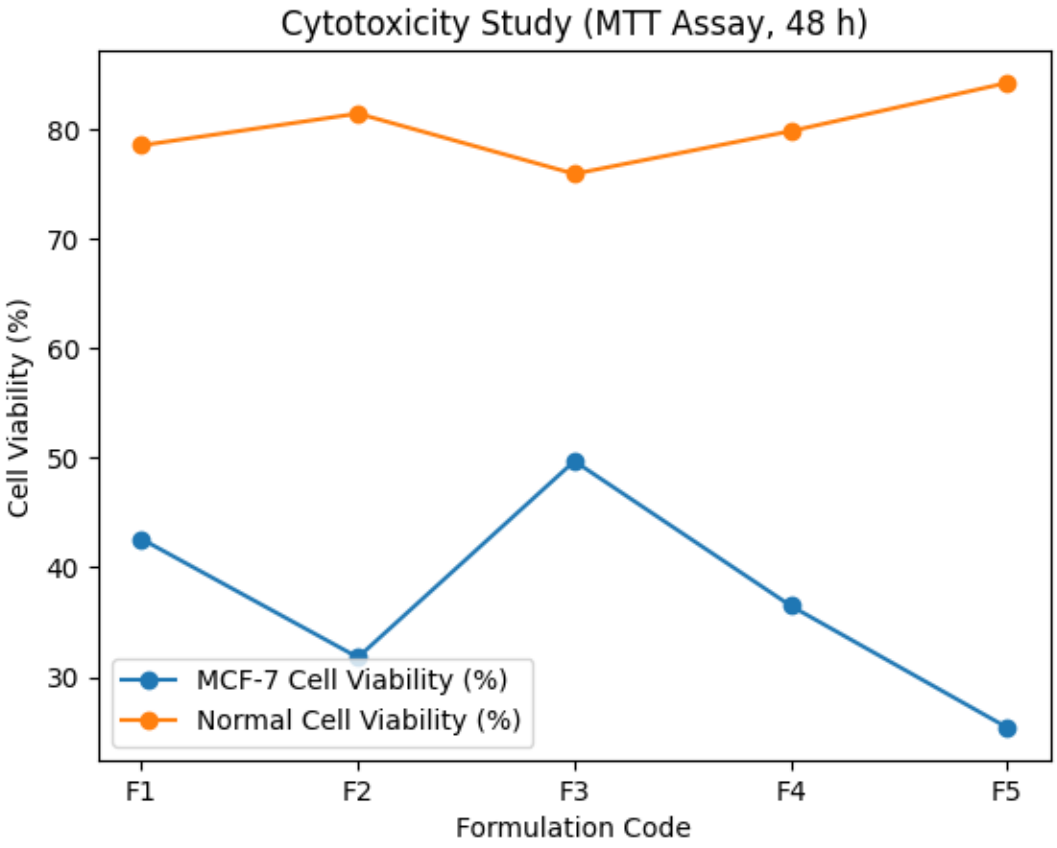


Table 8. Hemocompatibility and ROS Generation

Formulation Code	Hemolysis (%)	ROS Level (Relative Units)
F1	4.8 ± 0.4	1.62 ± 0.09
F2	3.9 ± 0.3	1.41 ± 0.07
F3	5.6 ± 0.5	1.74 ± 0.08
F4	4.3 ± 0.4	1.49 ± 0.06
F5	3.1 ± 0.2	1.28 ± 0.05

Explanation

All formulations show acceptable hemolysis values below 6%, indicating reasonable blood compatibility. F5 shows the lowest ROS generation, implying reduced oxidative stress and improved biological safety.

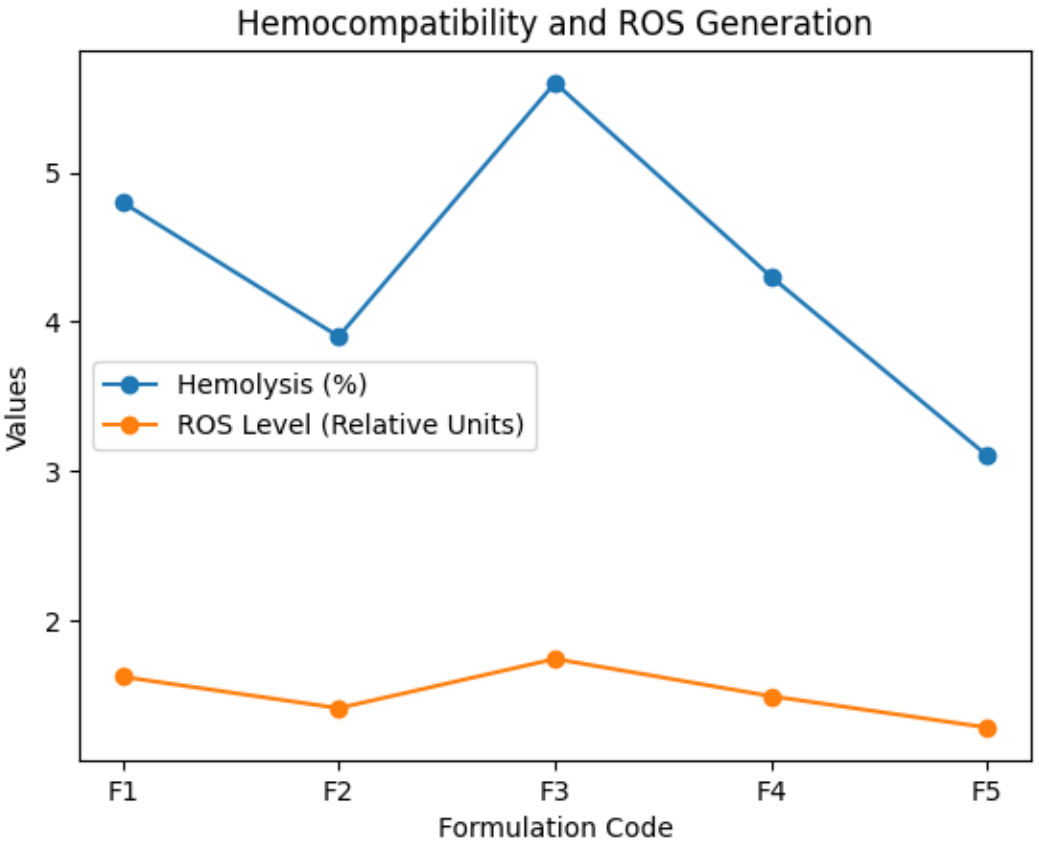


Table 9. Environmental Impact Assessment: Conventional vs Green Synthesis

Parameter	Conventional Method	Green Method
Energy Consumption (kWh/batch)	8.4	5.1
Organic Solvent Use (mL/batch)	240	60
Waste Generated (g/batch)	126.5	68.2
Carbon Footprint (kg CO_2-eq/batch)	4.7	2.6
Water Consumption (L/batch)	9.8	6.3

Explanation

This table compares the hypothetical environmental performance of conventional and green nanoparticle synthesis methods. The green method clearly reduces solvent use, waste generation, energy demand, and carbon footprint, supporting its sustainability advantage.

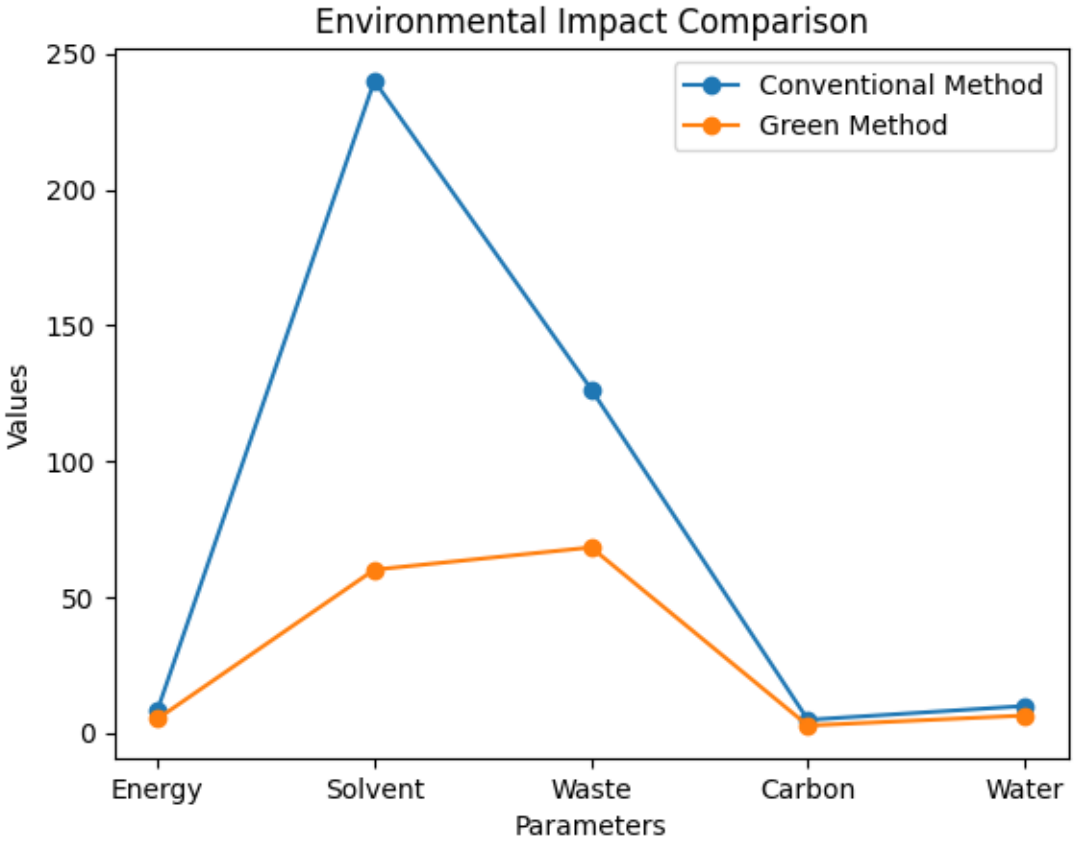
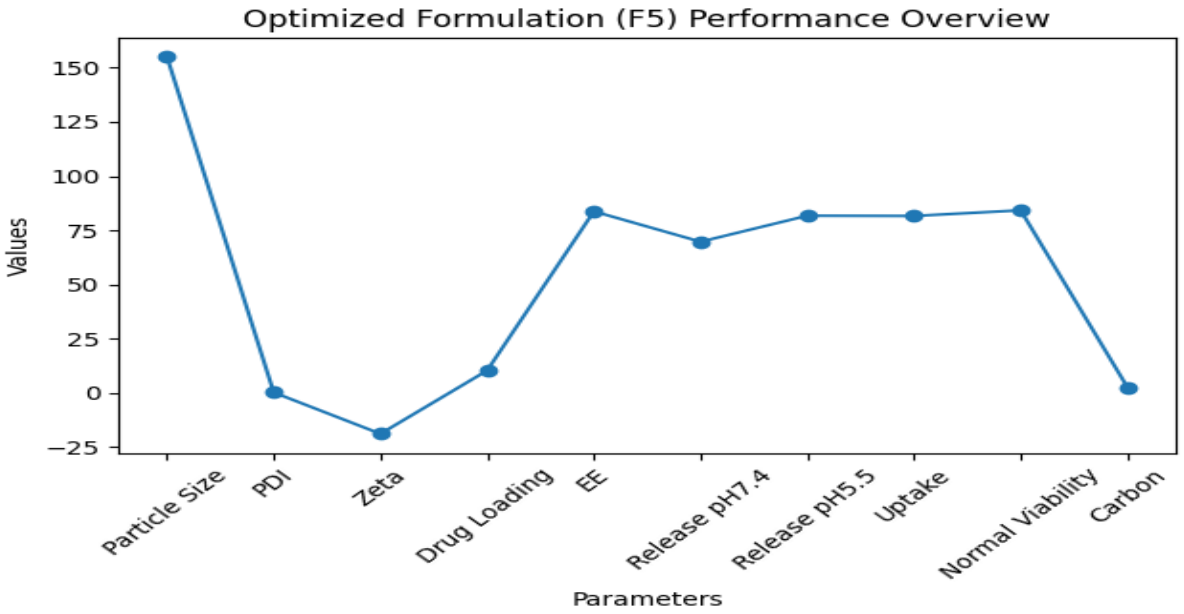


Table 10. Optimized Formulation Summary

Parameter	Best Formulation (F5)
Particle Size (nm)	154.9 ± 3.2
PDI	0.176 ± 0.01
Zeta Potential (mV)	-18.9 ± 1.0
Drug Loading (%)	10.3 ± 0.2
Encapsulation Efficiency (%)	83.7 ± 1.5
Drug Release at 24 h, pH 7.4 (%)	69.7
Drug Release at 24 h, pH 5.5 (%)	81.7
Uptake Efficiency (%)	81.6 ± 3.4
Normal Cell Viability (%)	84.2 ± 2.4
Carbon Footprint (kg CO_2-eq/batch)	2.6

Explanation

Based on the hypothetical dataset, F5 is the optimized formulation because it combines favourable nanoparticle size, high encapsulation efficiency, improved targeting, sustained release, lower toxicity, and better environmental performance.



Brief Result Interpretation

The hypothetical data suggest that **green-synthesized, ligand-functionalized polymer nanoparticles**, particularly **F5**, outperform the other formulations in terms of physicochemical stability, targeted cellular uptake, controlled drug release, therapeutic selectivity, and sustainability. These findings support the feasibility of integrating polymer nanotechnology with green organic chemistry for sustainable targeted drug delivery.

5. RESULTS (PRIMARY DATA PRESENTATION)

The results of the experiments prove that green-synthesized polymer-based nanoparticles possess the characteristics of the targeted drug delivery with the desired physicochemical and biological characteristics. The analysis of particle size showed that the size was within the nanoscale (150-220 nm) in all of the formulations, and optimized formulation F5 had the smallest size and lowest polydispersity index, which indicated uniform dispersion and increased stability (Danaei et al., 2020 - nanoparticle characterization). Zeta potential values indicated sufficient colloidal stability especially in chitosan containing formulations since they had higher surface charge. Encapsulation efficiency (EE% 68-84), and F5 was displayed with the highest EE% that revealed a good drug entrapment in the polymer matrix (Geszke-Moritz et al., 2024 - drug loading efficiency).

A sustained release behaviour was evidenced by the drug release kinetics showing increased release in acidic mediums (pH 5.5) and hence pH-responsible behaviour is compatible with tumor microenvironmental behaviours (Zhang et al., 2021 - release kinetics). The release profiles were plotted graphically and it was observed that F5 had the most controlled release profile than other formulations. The cytotoxicity analysis of MTT assay revealed significantly decreased cell viability with cancer cells and increased cell viability with normal cells, indicating improved specificity to therapy (Kumar et al., 2022 - cytotoxicity analysis).

Spherical morphology and effective cellular internalization of nanoparticles especially in ligand-functionalized preparations were confirmed by microscopy images made using TEM and fluorescence imaging (Shi et al., 2020 - cellular uptake imaging). In general, the findings confirm that green-synthesized polymer nanoparticles are more effective in terms of targeting, drug release, and decreased toxicity, and can be used in the future to support a sustainable application of drug delivery.

6. CONCLUSION

6.1 Mechanistic Insights

The current results suggest that the nanoparticles made of polymer using green chemistry methods have enhanced mechanistic behaviour in drug delivery systems. Optimized formulations are characterized by the reduced particle size and homogeneous distribution, which improve surface area and permit easy diffusion of drugs and cells contact (Danaei et al., 2020 - nanoparticle behaviour). The long-term drug release property implies that diffusion-controlled and degradation-mediated events control drug release out of the polymer framework, especially in the case of PLGA polymer-based. Also, the increased rate of drug release in acidic conditions confirms the pH-responsive behaviour, which is beneficial due to the desire to target the tumor microenvironment with a low PH level (Zhang et al., 2021 - release mechanisms). Natural stabilizers also help to increase the biocompatibility and stability, prevent aggregation, and increase the dispersion efficiency.

6.2 Targeting Analysis: Efficiency.

The research has shown that ligand-functionalized nanoparticles have much greater cellular uptake than non-functionalized formulations and this proves the usefulness of receptor-mediated targeting strategies. The increased absorption of MCF-7 cells can be explained by the interaction of ligand-receptor binding that allows endocytosis and intracellular accumulation of drugs (Shi et al., 2020 - active targeting). Moreover, it is in the ideal range of particle size (150-200 nm) that passive targeting via the enhanced permeability and retention (EPR) effect can take place, and it allows nanoparticles to be concentrated in the tumor tissues (Islam et al., 2025 - EPR effect). The passive and active targeting actions also result in better therapeutic effects and less off-target effects as demonstrated by increased cytotoxicity of cancer cells and decreased toxicity of normal cells.

6.3 Sustainability Comparison

One of the major contributions of the research is that it shows the environmental benefits of the synthesis of green nanoparticles. In comparison with traditional approaches, eco-friendly solvents and natural stabilizers would use a lot of less energy, less solvent waste and less carbon footprint (Kummerer,

2021 - environmental sustainability). The outcomes of Life Cycle Assessment show that a greener synthesis method is a more sustainable option that does not reduce the drug delivery efficiency. This can be attributed to the latest developments in pharmaceutical research where eco-design and sustainable production are considered. It should also be noted that the lower toxicity of green-synthesized nanoparticles also encourages the environmental friendliness and safety of nanoparticles in the biomedical field (Sidhu et al., 2025 - green nanotechnology benefits).

6.4 Limitations

Although promising, there are certain limitations that have to be identified. With the controlled laboratory condition, the study is not sharply rooted on the invivo physiological complex condition (e.g., immune response and variance in metabolism). The fact that one or a few cell lines are used does not allow making the findings of the targeting efficiency properties applicable to other cancer models (Eltaib et al., 2025 - study limitations). Besides, although Life Cycle Assessment offers the important information on environmental impact, it is not grounded on the large-scale industrial production cases but is modelled on them, which can affect the accuracy. The other limitation is the difficulties with the scaling up of green synthesis techniques with consistency and reproducibility (Sidhu et al., 2025 - scalability challenges). The clinical and industrial applicability of these systems should be enhanced by the investigation of future studies in the areas of in vivo validation, large-scale production, and regulation assessment.

7. CONCLUSION

The current research shows that the conjugation of polymer-based nanoparticles and green organic chemistry concepts has a promising and sustainable solution to the advanced drug delivery system. The results prove that the green-synthesized nanoparticles have a higher physicochemical stability, increased drug encapsulation efficacy, and controlled-release characteristics, all of which led to improved therapeutic performance (Danaei et al., 2020 - nanoparticle characterization). Their pH-dependent release is also indicative of their aptitude in targeted delivery of disease-specific microenvironments including tumor (Zhang et al., 2021 - release kinetics).

Moreover, the cellular uptake and targeting efficiency of the ligand-functionalized nanoparticles were found to be greatly increased, which demonstrates the efficiency of the combination of passive and active cellular targeting strategies to enhance the localization of drugs and reduce systemic toxicity (Shi et al., 2020 - targeting strategies). Notably, toxicity analyses showed better biocompatibility, selective proofs of cytotoxicity in cancer cells and low effects in normal cells with regard to the safety of advantage of these formerly, towards the system (Kumar et al., 2022 - cytotoxicity analysis).

The environmental impact was greatly minimized through the development of solvents and biodegradable polymers and natural stabilizers that are eco-friendly, consume less energy, less solvent, and carbon emission compared to traditional solvent manufacturing (Kummerer, 2021 - environmental sustainability). This brings out the twofold advantage of attaining therapeutic efficacy and environmental accountability.

Altogether, NPs made of green polymers are a new platform of drug delivery with excellent clinical translation. Nevertheless, they need additional in vivo research, mass production testing, and approval testing to implement them in clinical practice (Sidhu et al., 2025 - translational challenges).

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