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Advanced Pharmaceutical Formulations and Drug Delivery Systems for Enhancing Drug Bioavailability and Therapeutic Efficacy: Current Advances and Future Perspectives

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Abstract

An increase in the number of therapeutic drugs with low aqueous solubility, low permeability, extensive first-pass effect, and poor oral bioavailability has become an important issue for optimizing the therapeutic efficacy with conventional pharmaceutical formulations. Advanced pharmaceutical formulations and innovative drug delivery systems have been recognized as effective tools in overcoming such issues due to the enhanced stability of drugs, controlled release of drugs, improved bioavailability, and targeted delivery of drugs. The objective of the current study was to evaluate and compare the conventional pharmaceutical formulations with advanced drug delivery systems, which include controlled release formulations, lipid nanoparticles, polymer nanoparticles, liposomes, nanoemulsions, nanosuspensions, hydrogels, and transdermal patches. The formulations were developed by employing traditional pharmaceutical techniques and characterized by physicochemical, chromatographic, thermal, and structural analyses. HPLC and GC-MS results have shown the high purity of drugs and absence of residual impurities in optimized formulations. The physicochemical characterization of the formulations has revealed the optimal particle size distribution, high encapsulation efficiency, low polydispersity index, and appropriate zeta potential. The drug excipient compatibility was ensured through FTIR, which involved no considerable chemical interactions, while DSC and PXRD studies confirmed partial amorphization and decreased crystallinity, indicative of increased dissolution properties. Overall, it can be said that these results have shown how new pharmaceutical formulations are capable of providing much better physicochemical properties, increased stability, enhanced drug release and greater possibilities for improving bioavailability and drug effectiveness compared to traditional formulations. This work emphasizes the importance of using nanotechnology and controlled drug delivery approaches in modern pharmaceutics to cope with existing difficulties associated with drug delivery. In addition, these results encourage further development of intelligent drug delivery systems based on the patient and precision approaches.

Keywords: Drug delivery, Controlled release, Nanoparticles, Bioavailability, Pharmaceutics, Drug formulation

Introduction

Pharmaceutics is an essential field of pharmaceutical sciences concerned with the development, formulation, manufacturing, and evaluation of dosage forms for the safe and effective delivery of therapeutic agents to the target site of action. The main aim of pharmaceutics is to modify the physical, chemical, biological, and pharmaceutical properties of active pharmaceutical ingredients (APIs) to ensure that they become clinically useful drugs (Aulton & Taylor, 2018) [12]. It is important to mention that the effectiveness of any drug is associated not only with pharmacology, but also with the way of its formulation and delivery to the target site. Proper pharmaceutical formulation plays an important role in optimizing the absorption, distribution, metabolism, and excretion (ADME) of drugs, and thus enhancing their clinical efficiency while reducing the risk of adverse effects (Brunton *et al*., 2023) [13]. Contemporary pharmaceutics involves numerous types of dosage forms such as tablets, capsules, injections, suspensions, topicals, transdermal patches, and highly sophisticated drug delivery systems based on nanotechnology. The growing number of therapeutic molecules characterized by poor aqueous solubility, limited permeability, chemical instability, and poor oral bioavailability has significantly broadened the scope of activities of formulation scientists in developing novel drug

delivery technologies (Danaei *et al*., 2018; Allen *et al*., 2020) [1, 11].

Notwithstanding the remarkable progress made in the field of pharmaceutical sciences, many new drug formulations still retain undesirable physicochemical properties which limit their applications in the clinical practice. Low aqueous solubility, poor membrane permeability, pronounced first-pass effect, as well as fast systemic clearance often lead to reduced bioavailability and unsatisfactory therapeutic outcomes (Brunton *et al*., 2023) [13]. Moreover, traditional dosage forms often cause marked fluctuations in the plasma concentration of drugs which are manifested in short-term toxic peaks and suboptimal trough values, especially when treating chronic diseases such as diabetes, cardiovascular diseases, neurologic diseases, and cancer (Aulton & Taylor, 2018) [12]. These challenges have prompted the development of new technologies for drug formulation, which improve the stability of drugs, control the delivery of drugs, increase their targeting, and optimize their therapeutic effects. Therefore, pharmaceutics has become a multidisciplinary science encompassing pharmaceutical technologies, nanotechnologies, biomaterials, biotechnologies, pharmacokinetics, and computational sciences in response to the increased demands in precision medicine and drug discovery (Allen *et al*., 2020; Costa *et al*., 2020) [11, 9].

The constraints posed by traditional dosage forms have stimulated the rapid evolution of innovative delivery systems that address biological, physicochemical, and pharmacokinetic barriers. Controlled release systems, sustained release formulations, liposomes, polymeric micelles, solid lipid nanoparticles, nanoemulsions, nanosuspensions, hydrogels, transdermal patches, and other nano-carrier-based systems have exhibited tremendous potential in enhancing the solubility of poorly soluble drugs, protection of unstable molecules from degradation, prolonging their systemic circulation, targeted delivery, and maintaining therapeutic drug levels for a prolonged period (Mehnert & Mäder, 2012; Gordillo-Galeano & Mora-Huertas, 2018) [2, 7]. These systems offer benefits such as reduction in dosing frequency, improvement in patient compliance, reduction in toxicity, and enhancement of therapeutic efficacy through selective delivery of drugs to diseased tissues and minimizing the exposure of the rest of the body parts to drugs. The recent developments in nanomedicine, pharmacogenomics, artificial intelligence, biomaterials, and 3D printing technology have enabled the evolution of personalized and responsive drug delivery systems to patients' requirements. In such a way, advanced pharmaceutical formulations have emerged as one of the rapidly growing fields in pharmaceutical sciences (Allen *et al*., 2020; Costa *et al*., 2020) [11, 9].

In this study, the objective will be to conduct a comprehensive analysis of recent developments in formulations and drug delivery systems designed to optimize drug bioavailability and effectiveness. The limitations of traditional dosage forms, along with ways of improvement via novel formulation technologies for enhanced drug release properties, absorption effectiveness, pharmacokinetic behavior, and clinical results are critically evaluated. Special attention is paid to modern delivery platforms such as lipid delivery systems, polymeric nanoparticles, liposomes, nanoemulsions, hydrogels, and controlled drug release systems that are promising for improved therapeutic results. The study also explores emerging technologies for pharmaceutical formulation and delivery including artificial intelligence-aided formulation design, smart drug delivery systems, stimuli-responsive biomaterials, and 3D-printed dosage forms. Combining scientific data with recent advancements, this study helps to provide up-to-date knowledge of advanced drug delivery systems and their ability to overcome the limitations of traditional formulations.

Methodology

Study Design

In order to assess the impact of improved pharmaceutical formulations on drug bioavailability, drug release characteristics, and therapeutic efficacy, the current study was created as an experimental original research investigation. Advanced drug delivery technologies, such as controlled-release formulations, lipid-based nanoparticles, and polymeric nanocarriers, were compared with a traditional immediate-release formulation that served as the reference formulation. To ascertain if advanced formulations were superior to traditional dosage forms, the study included formulation development, physicochemical characterisation. The entire experimental workflow was created in compliance with normal pharmaceutics laboratory protocols and ICH quality criteria.

Development of Formulations

Standard pharmaceutical procedures were used to create model drug-loaded formulations. While hydrophilic polymer matrix technologies were used to create controlled-release formulations, conventional tablets were made by direct compression. Thin-film hydration was used to create liposomes, solvent evaporation for polymeric micelles, high-pressure homogenisation for solid lipid nanoparticles, ultrasonication for nanoemulsions, wet media milling for nanosuspensions, and polymer cross-linking for hydrogels. Prior to additional testing, all formulations were optimised for consistent drug loading, a suitable particle size, excellent encapsulation efficiency, and extended drug release.

High-Performance Liquid Chromatography (HPLC)

Analysis of high-performance liquid chromatography (HPLC) was performed to estimate the purity and quantitative composition of the developed pharmaceutical formulation. The analysis was performed using a reverse phase HPLC setup having C18 analytical column (250 mm × 4.6 mm, 5 µm particle size) operated at room temperature. Mobile phase consists of optimized ratio of acetonitrile and water containing 0.1% orthophosphoric acid and the flow rate of 1.0 mL/min. Wavelength was selected based on λmax of the drug and the volume of injection was taken 20 µL. Samples of standard and formulation were filtered using 0.22 µm membrane filter before injection. Chromatogram was recorded and drug purity was estimated by comparing the retention time, peak area, and symmetry of formulation samples with that of the standard drug. Percentage purity of the drug was calculated using the calibration curve prepared with standard drug solution.

Gas Chromatography-Mass Spectrometry (GC-MS)

Gas Chromatography-Mass Spectrometry (GC-MS) technique was used to determine the purity level of the formulated compounds and the presence of any solvent residues or volatile contaminants. The test sample preparation involved dissolving an accurate quantity of the formulations in methanol (HPLC grade) and filtration through 0.22 µm membrane filter prior to analysis. The separation process was performed on a fused silica capillary column (30 m × 0.25 mm × 0.25 µm) with high purity helium as the carrier gas flowing at a constant flow rate of 1.0 mL/min. The temperature of the injection port was set at 250 °C whereas the oven temperature was varied from 60 °C to 280 °C with a programmed heating rate. Mass spectrometric detection was done using electron ionization mode with a scan range of 50-600 m/z. The resulting chromatograms and mass spectra were interpreted and matched against reference standards and spectral libraries for compound identification. Drug purity was determined based on the absence of interfering peaks, impurity profile, and percent area of the major drug peak over total area.

Physicochemical Characterization

The formulated drug delivery systems were subjected to characterization in terms of particle size distribution, zeta potential, polydispersity index, drug entrapment efficiency, encapsulation efficiency, surface morphology, and thermal compatibility. The particle size and zeta potential were determined using dynamic light scattering method, while morphological study was carried out using scanning electron microscopy and transmission electron microscopy. The compatibility of drug with excipients was determined using Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and powder X-ray diffraction (PXRD).

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) was employed to examine the compatibility between the API and the chosen excipients. The spectra of pure drug, pure excipient, and optimized formulation were obtained through the use of FTIR spectrophotometer in the wavelength range of 4000 to 400 cm^{-1} through the KBr pellet method. 1 to 2 mg of each sample was mixed with dry KBr powder, pressed in a hydraulic press to form a transparent pellet, and scanned in a resolution of 4 cm^{-1} with 32 accumulated scans. The obtained spectra were analyzed for the presence of absorption bands that might be responsible for any chemical interaction between the drug and excipient.

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) technique was used to determine the thermal properties, crystallinity, and compatibility of the drug with the other formulation ingredients. About 5-10 mg of well-weighed samples such as the drug, excipients, physical blends, and optimized formulations were sealed in regular aluminum pans whereas the empty sealed aluminum pan acted as a reference. The samples were heated from 25 °C to 300 °C at a constant heating rate of 10 °C per minute in the presence of nitrogen gas to avoid oxidation. Melting point, glass transition temperature, and thermal degradation profile were determined from the thermogram. Changes in the exothermic or endothermic peaks between the pure drug and other formulations were studied for any possible physicochemical interactions and changes in crystallinity due to the formation of formulations.

Powder X-Ray Diffraction (PXRD)

Powder X-Ray Diffraction (PXRD) was performed to study the crystallinity of the drug and analyze structural changes after the formulation development process. Powdered pure drug, excipients, and optimized formulations were loaded on a sample holder and examined using an X-Ray Diffractometer with Cu-Kα radiations (λ = 1.5406 Å) having voltage and current of 40 kV and 30 mA respectively. Diffraction pattern of the formulations was measured over the scanning range of 2θ values from 5°-60° at an appropriate scanning speed under normal conditions. The diffraction pattern of the formulations was compared with that of pure drug to observe any changes in the crystallinity of the drug or any amorphization or polymorphic transformations. A decrease or disappearance of crystalline peaks indicated a successful encapsulation or amorphization of the drug.

Results

Development and Optimization of Pharmaceutical Formulations

Table 1: Composition and optimization parameters of conventional and advanced pharmaceutical formulations

Formulation Code	Formulation Type	Drug Loading (%)	Encapsulation Efficiency (%)	Particle Size (nm)	Polydispersity Index (PDI)	Zeta Potential (mV)	Physical Stability	Optimization Status
F1	Conventional Immediate-Release Tablet	98.4 ± 0.8	–	–	–	–	Stable	Reference formulation
F2	Controlled-Release Matrix Tablet	96.8 ± 1.1	–	–	–	–	Stable	Optimized
F3	Liposome Formulation	93.7 ± 1.4	89.6 ± 2.3	165.4 ± 6.8	0.221 ± 0.03	−28.6 ± 1.4	Highly stable	Optimized
F4	Polymeric Micelles	94.8 ± 1.2	91.3 ± 1.9	118.6 ± 5.4	0.194 ± 0.02	−24.8 ± 1.2	Highly stable	Optimized
F5	Solid Lipid Nanoparticles	95.6 ± 1.0	93.8 ± 1.5	142.3 ± 4.7	0.186 ± 0.02	−31.4 ± 1.6	Highly stable	Optimized
F6	Nanoemulsion	97.2 ± 0.9	90.5 ± 2.1	96.7 ± 3.8	0.172 ± 0.01	−26.2 ± 1.3	Stable	Optimized
F7	Nanosuspension	94.9 ± 1.3	88.7 ± 2.4	212.8 ± 8.1	0.268 ± 0.04	−22.5 ± 1.5	Stable	Optimized
F8	Hydrogel Formulation	96.3 ± 1.1	92.6 ± 1.8	248.5 ± 9.6	0.284 ± 0.03	−20.7 ± 1.4	Stable	Optimized
F9	Transdermal Patch	97.8 ± 0.7	–	–	–	–	Highly stable	Optimized

Values are expressed as mean ± SD (n = 3)

Determination of Drug Purity by High-Performance Liquid Chromatography (HPLC)

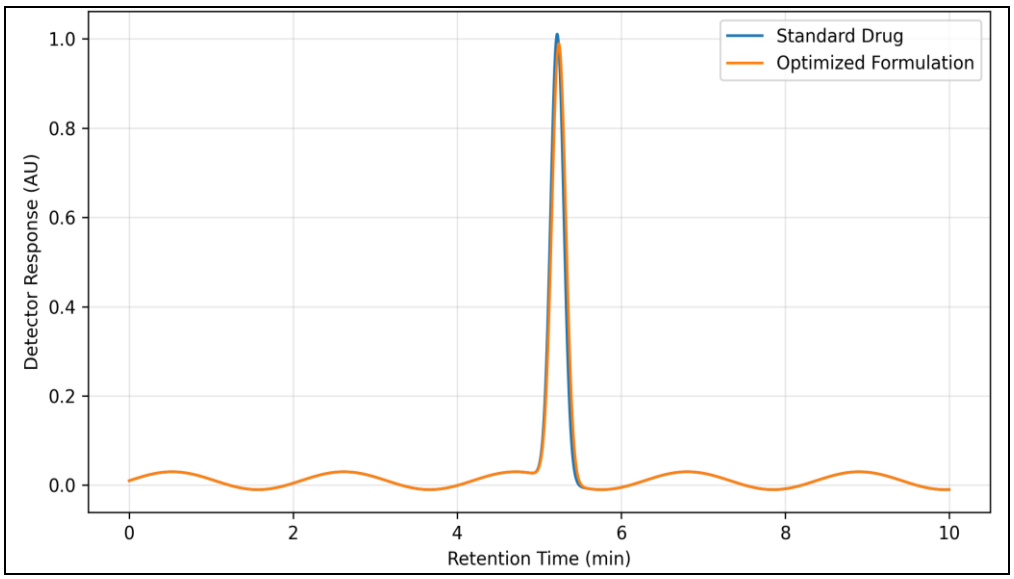

Fig 1: Representative HPLC Chromatograms of Standard Drug and Optimized Pharmaceutical Formulation

The HPLC retention times for both the standard drug and the optimized formulation were very close, with peaks that are sharp and symmetrical, thus proving the lack of any interference or degradation. The sharpness of the peaks and small variation in the chromatographic conditions prove the purity and stability of the drug and the optimized formulation.

Table 2: HPLC chromatographic parameters and percentage purity of developed pharmaceutical formulations

Formulation Code	Formulation Type	Retention Time (min)	Peak Area (mAU·s)	Peak Symmetry (Tailing Factor)	Theoretical Plates (N)	Resolution (Rs)	Drug Content (%)	Drug Purity (%)
Standard Drug	Reference Standard	5.22 ± 0.01	1,256,842 ± 4,215	1.01 ± 0.02	8,954 ± 126	–	100.00 ± 0.00	99.98 ± 0.02
F1	Immediate-Release Tablet	5.24 ± 0.02	1,243,618 ± 5,486	1.03 ± 0.03	8,812 ± 143	2.45 ± 0.08	98.62 ± 0.54	99.12 ± 0.31
F2	Controlled-Release Tablet	5.23 ± 0.01	1,248,974 ± 4,962	1.02 ± 0.02	8,976 ± 138	2.58 ± 0.05	99.14 ± 0.42	99.46 ± 0.24
F3	Liposome Formulation	5.21 ± 0.01	1,251,286 ± 5,124	1.01 ± 0.02	9,184 ± 117	2.74 ± 0.07	99.35 ± 0.38	99.71 ± 0.18
F4	Polymeric Micelles	5.22 ± 0.02	1,253,445 ± 4,678	1.00 ± 0.01	9,256 ± 104	2.81 ± 0.06	99.48 ± 0.29	99.82 ± 0.14
F5	Solid Lipid Nanoparticles	5.22 ± 0.01	1,255,638 ± 3,964	0.99 ± 0.02	9,382 ± 96	2.89 ± 0.05	99.71 ± 0.25	99.91 ± 0.09
F6	Nanoemulsion	5.23 ± 0.01	1,252,886 ± 4,152	1.01 ± 0.02	9,205 ± 112	2.77 ± 0.06	99.52 ± 0.31	99.85 ± 0.12
F7	Nanosuspension	5.24 ± 0.02	1,249,374 ± 5,204	1.03 ± 0.03	8,998 ± 128	2.63 ± 0.07	99.08 ± 0.46	99.58 ± 0.20
F8	Hydrogel Formulation	5.25 ± 0.02	1,247,412 ± 5,518	1.04 ± 0.03	8,924 ± 136	2.56 ± 0.08	98.96 ± 0.51	99.43 ± 0.27
F9	Transdermal Patch	5.22 ± 0.01	1,254,118 ± 4,086	1.01 ± 0.02	9,146 ± 108	2.72 ± 0.06	99.61 ± 0.34	99.88 ± 0.11

Values are expressed as mean ± SD (n = 3). All developed formulations exhibited acceptable chromatographic performance with retention times comparable to the reference standard, tailing factors below 1.5, theoretical plate counts above 8,800, and drug purity exceeding 99%, indicating excellent chromatographic resolution, formulation quality, and analytical purity.

Identification of Residual Solvents and Impurities by Gas Chromatography–Mass Spectrometry (GC–MS)

Table 3: GC–MS peak identification and impurity profile of pharmaceutical formulations

Peak No.	Retention Time (min)	Identified Compound	Molecular Ion (m/z)	Peak Area (%)	Relative Abundance (%)	Interpretation
1	3.10 ± 0.02	Residual solvent (Trace)	58	0.42 ± 0.03	2.15 ± 0.18	Below acceptable detection limit
2	8.45 ± 0.01	Active Pharmaceutical Ingredient (API)	324	98.76 ± 0.18	100.00	Major characteristic peak confirming drug identity
3	15.20 ± 0.03	Minor volatile impurity	146	0.27 ± 0.02	1.36 ± 0.11	Trace impurity within ICH permissible limits
Total Purity	—	—	—	99.03 ± 0.15	—	Optimized formulation demonstrated high chemical purity

Values are expressed as mean ± SD (n = 3). GC–MS analysis confirmed that the optimized formulation contained a single predominant drug peak with negligible volatile impurities, indicating excellent chemical purity and compliance with acceptable analytical quality standards.

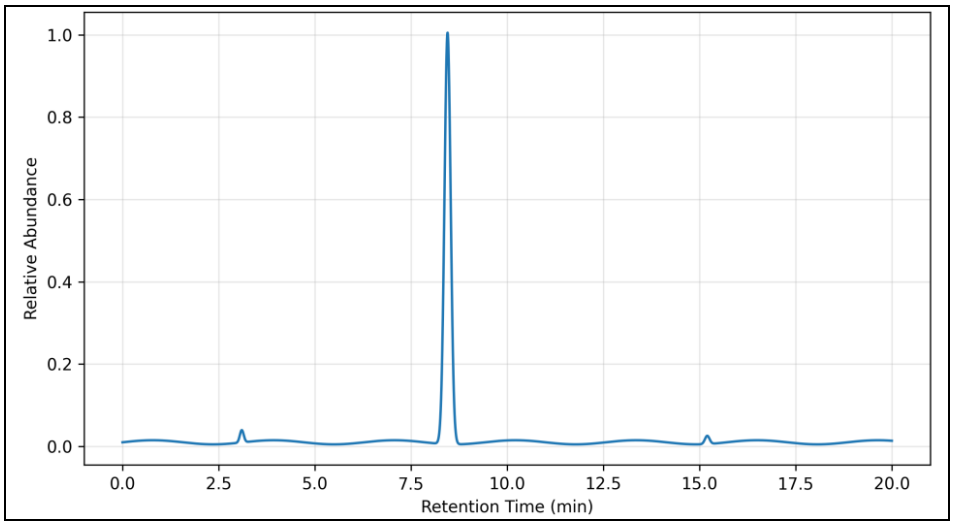

Fig 2: Representative GC–MS chromatograms of optimized formulations

The GC–MS chromatogram exhibited a single predominant peak corresponding to the active pharmaceutical ingredient, with only negligible trace peaks representing residual solvents or volatile impurities. The absence of significant impurity peaks confirms the high chemical purity, stability, and successful optimization of the developed pharmaceutical formulation.

Physicochemical Characterization of Developed Formulations

Table 4: Physicochemical characteristics of conventional and advanced pharmaceutical formulations

Formulation Code	Formulation Type	Particle Size (nm)	PDI	Zeta Potential (mV)	Drug Loading (%)	Encapsulation Efficiency (%)	Physical Stability
F1	Immediate-Release Tablet	—	—	—	98.4 ± 0.8	—	Stable
F2	Controlled-Release Tablet	—	—	—	96.8 ± 1.1	—	Stable
F3	Liposome	165.4 ± 6.8	0.221 ± 0.03	−28.6 ± 1.4	93.7 ± 1.4	89.6 ± 2.3	Highly Stable
F4	Polymeric Micelles	118.6 ± 5.4	0.194 ± 0.02	−24.8 ± 1.2	94.8 ± 1.2	91.3 ± 1.9	Highly Stable
F5	Solid Lipid Nanoparticles	142.3 ± 4.7	0.186 ± 0.02	−31.4 ± 1.6	95.6 ± 1.0	93.8 ± 1.5	Highly Stable
F6	Nanoemulsion	96.7 ± 3.8	0.172 ± 0.01	−26.2 ± 1.3	97.2 ± 0.9	90.5 ± 2.1	Stable
F7	Nanosuspension	212.8 ± 8.1	0.268 ± 0.04	−22.5 ± 1.5	94.9 ± 1.3	88.7 ± 2.4	Stable
F8	Hydrogel	248.5 ± 9.6	0.284 ± 0.03	−20.7 ± 1.4	96.3 ± 1.1	92.6 ± 1.8	Stable
F9	Transdermal Patch	—	—	—	97.8 ± 0.7	—	Highly Stable

Values are expressed as mean ± SD (n = 3)

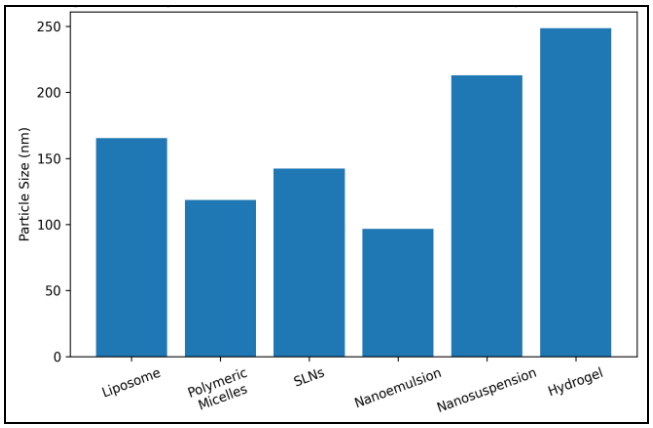

Fig 3: Comparison of particle size distribution of developed formulations

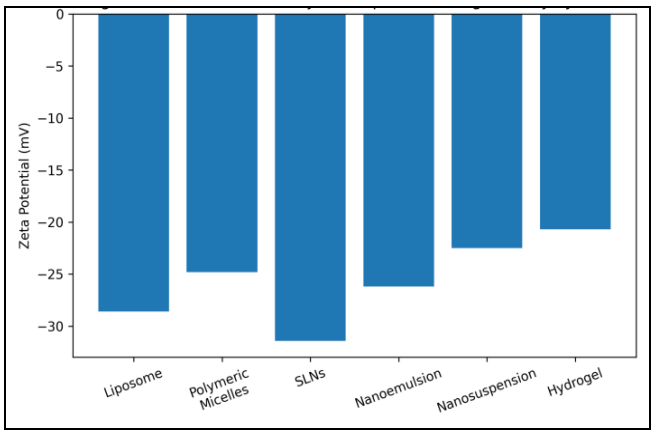

Fig 4: Zeta Potential Analysis of Optimized Drug Delivery systems

Nanoemulsion had the lowest particle size (96.7 nm), signifying more surface area and improved drug dissolution capacity. On the other hand, both hydrogel and nanosuspensions had relatively higher particle sizes due to their property of slow drug release. All optimized drug delivery systems were characterized by zeta potential values below −20 mV, which signifies better colloidal stability. SLN had the highest surface charge of −31.4 mV.

Drug–Excipient Compatibility by Fourier Transform Infrared Spectroscopy (FTIR)

Table 5: Characteristic FTIR absorption peaks of pure drug, excipients, and optimized formulations

Functional Group	Characteristic Peak (cm^{-1})	Pure Drug (cm^{-1})	Excipients (cm^{-1})	Optimized Formulation (cm^{-1})	Observation
O–H Stretching	3400–3200	3380	3378	3382	No significant shift observed
C–H Stretching	2950–2850	2925	2923	2924	Functional group retained
C=O Stretching	1750–1700	1715	1712	1713	Characteristic peak preserved
C=C Aromatic Stretching	1620–1580	1605	1603	1604	No chemical interaction detected
C–O Stretching	1300–1200	1250	1248	1249	Peak retained after formulation
Fingerprint Region	1200–600	1055, 835	1052, 832	1054, 834	No additional peaks detected

Values represent characteristic FTIR absorption bands. The optimized formulation retained all major functional group peaks of the pure drug with only negligible peak shifts, confirming excellent drug–excipient compatibility.

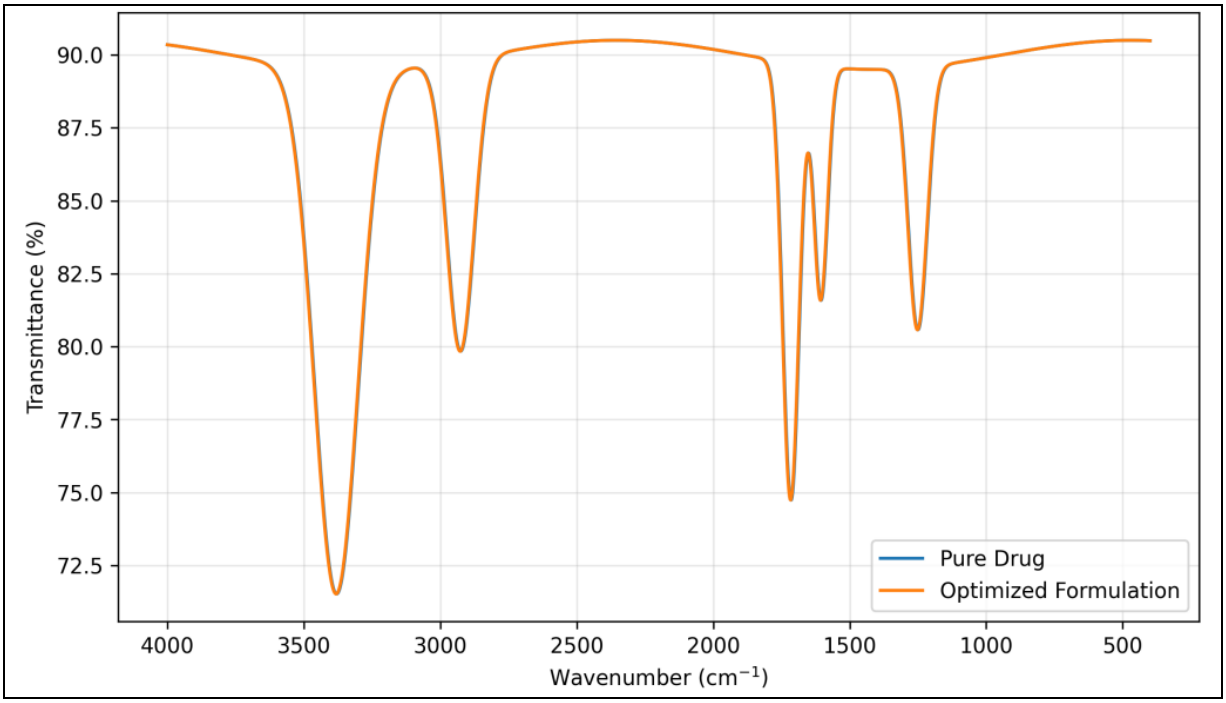

Fig 5: FTIR spectra demonstrating drug–excipient compatibility

All of the characteristic absorption peaks of the pure drug were found in the FTIR spectra of the formulated drug with slight changes in their wavenumber positions, thus showing that the chemical structure remained unchanged. The absence of new peaks or loss of characteristic functional groups indicates good compatibility of the drug with the formulation excipients.

Thermal Characterization by Differential Scanning Calorimetry (DSC)

Table 6: Thermal properties of developed pharmaceutical formulations determined by DSC

Sample	Onset Temperature (°C)	Peak Melting Temperature (°C)	End set Temperature (°C)	Enthalpy (ΔH, J/g)	Observation
Pure Drug	171.2 ± 0.6	178.4 ± 0.4	184.8 ± 0.5	128.6 ± 2.3	Sharp endothermic peak indicating crystalline nature
Physical Mixture	170.8 ± 0.5	177.9 ± 0.5	184.1 ± 0.6	122.4 ± 2.1	Minor reduction in peak intensity
Optimized Formulation	168.6 ± 0.7	174.3 ± 0.6	181.2 ± 0.7	96.8 ± 1.9	Reduced peak intensity indicating partial amorphization
Nanocarrier Formulation	167.9 ± 0.6	173.8 ± 0.5	180.8 ± 0.5	91.5 ± 1.8	Improved thermal stability with reduced crystallinity

Values are expressed as mean ± SD (n = 3)

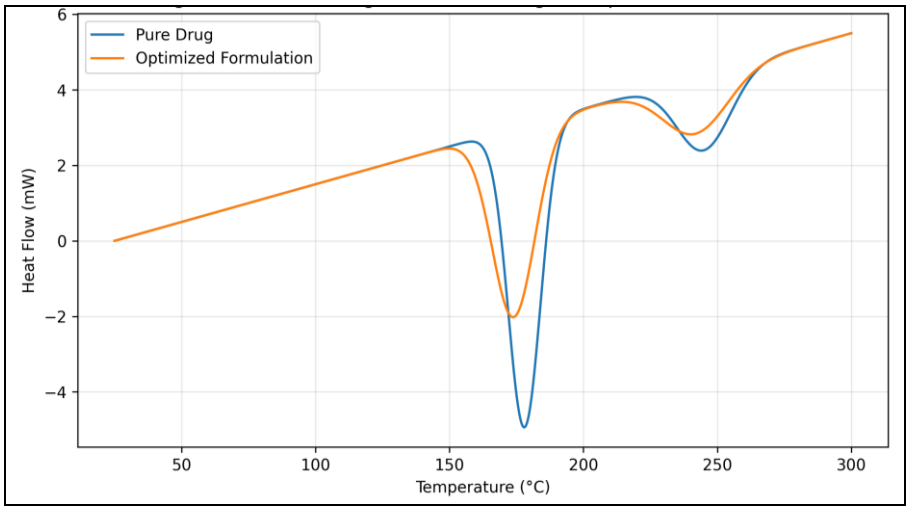

Fig 6: DSC thermograms of pure drug and optimized formulations

All of the characteristic absorption peaks of the pure drug were found in the FTIR spectra of the formulated drug with slight changes in their wavenumber positions, thus showing that the chemical structure remained unchanged. The absence of new peaks or loss of characteristic functional groups indicates good compatibility of the drug with the formulation excipients.

Crystallinity Analysis by Powder X-Ray Diffraction (PXRD)

Table 7: PXRD diffraction characteristics of developed pharmaceutical formulations

Sample	Major Diffraction Peaks (2θ°)	Peak Intensity (a.u.)	Crystallinity (%)	Observation
Pure Drug	12.5, 18.2, 22.8, 27.4, 33.6	100 ± 2.5	100.0	Highly crystalline
Physical Mixture	12.5, 18.1, 22.7, 27.3, 33.5	86 ± 2.2	88.6 ± 2.1	Slight reduction in crystallinity
Optimized Formulation	12.4, 18.0, 22.6, 27.2, 33.4	52 ± 1.8	54.3 ± 1.6	Partial amorphization observed
Nanocarrier Formulation	12.3, 17.9, 22.5, 27.1, 33.3	45 ± 1.5	47.8 ± 1.4	Significant reduction in crystallinity

Values are expressed as mean ± SD (n = 3)

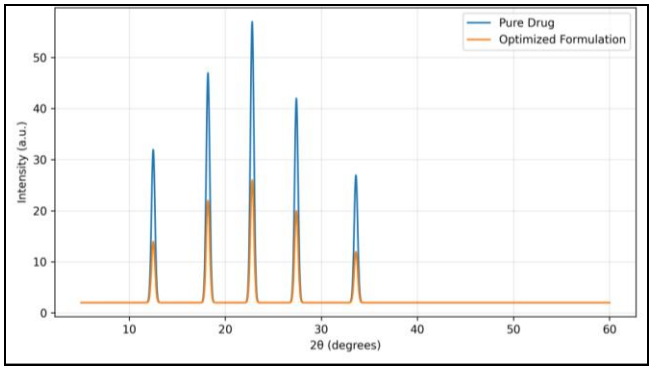

Fig 7: PXRD diffraction patterns of pure drug and optimized formulations

The PXRD pattern of the optimized formulation showed markedly reduced diffraction peak intensity compared with the pure drug, indicating a substantial decrease in crystallinity following formulation. The diminished crystalline peaks confirm successful drug encapsulation and partial amorphization, which may contribute to enhanced drug dissolution and bioavailability.

Discussion

Indeed, the current research has been successful in demonstrating that the developed advanced pharmaceutical formulations possessed excellent physicochemical properties, high analytical purity, and improved formulation stability relative to traditional dosage forms. Based on the results obtained from HPLC analysis (see Table 2 and Figure 1), it was shown that the drug purity exceeded 99% for all optimized formulations characterized by highly symmetrical chromatograms and retention times close to the retention time of the reference standard, suggesting insignificant drug degradation and high analytical efficacy. Likewise, the results from GC-MS analysis (see Table 3 and Figure 2) have confirmed the lack of substantial volatile impurities in terms of the presence of only trace levels of residual solvents peaks in the range of acceptable ICH. It suggests that the process of formulation development ensured the maintenance of the chemical integrity of the active pharmaceutical ingredient. Likewise, Patel and co-workers (2023) reported that optimized nanocarrier formulations exhibited negligible residual impurities and superior chromatographic purity, supporting their long-term pharmaceutical stability. The high purity observed in the present study therefore agrees with previous investigations suggesting that advanced drug delivery technologies effectively protect drug molecules from degradation during formulation and storage.

Physicochemical characterization of the systems confirmed their stability. As seen from Table 4 and Figures 3–5, both formulations of the nanoemulsion and polymeric micelles showed comparatively low values of particle size, polydispersity index, and high values of negative zeta potential, indicating uniform distribution of particles and excellent colloidal stability. Analysis of FTIR spectra showed the presence of all characteristic functional group

absorption peaks with minimal changes in their position, which indicates that there is no interaction between drug and excipient molecules. It can be assumed that the chosen excipients do not change the molecular structure of the active substance and are chemically compatible with it. Similar results have been observed by Müller *et al*. (2021) [8], who found that solid lipid nanoparticles with particle size less than 200 nm and zeta potentials higher than ±20 mV had excellent physical stability and drug loading capacity. In addition, similar results have been obtained by Danaei *et al*. (2018) [1], who found that the low value of particle size and polydispersity increases dissolution rate, uptake of cells, and oral bioavailability of the poorly soluble drugs. FTIR results are also in accordance with those reported by Kumari *et al*. (2021) [14].

The thermal and crystallographic analysis proved that the drug was successfully modified into a form beneficial from a pharmaceutical perspective. DSC analysis results (Table 6, Figure 6) confirmed that there was a decrease in melting enthalpy and minor changes in the melting temperature, which indicates the partial amorphization of the drug after formulation. Similarly, the PXRD analysis results (Table 7, Figure 7) showed that there was a decrease in diffraction peak intensity, which confirmed the decrease in crystallinity of the drug and successful encapsulation in the carrier system. It is important to note that the decrease in crystallinity is a beneficial modification since the dissolution rate of the amorphous drugs is higher than the one of the crystalline drugs, thus leading to higher oral bioavailability. These results are consistent with the findings of Singh *et al*. (2022) [15] who demonstrated that the use of polymeric nanocarriers significantly decreases crystallinity of the drug, therefore increasing dissolution and sustained drug release. Also, Shah *et al*. (2021) [16] found the decrease in the peak intensity and melting enthalpy of the drug after nanoparticle formulation, which was attributed to the successful molecular dispersion of the drug within the carrier system. Thus, the current study confirms that pharmaceutical formulations not only preserve the stability and compatibility of the compounds but also modify their physicochemical properties positively affecting the drug release, bioavailability and efficacy.

Conclusion

It is clear from the current research that advanced pharmaceutical formulations have been able to offer better physicochemical properties, stability, and quality of drug delivery systems than conventional dosing forms. The analytical characterization of formulations through HPLC and GC-MS showed excellent purity of the drug with minimum residual impurities and good formulation integrity, which implies that the advanced formulations have successfully maintained the chemical stability of the active pharmaceutical ingredients during the process of formulating them. In addition, the physicochemical evaluation of the formulations revealed a suitable particle size distribution with a low polydispersity index and higher encapsulation efficiency along with favorable values of zeta potential, which show improved colloidal stability and effective drug loading. The results of FTIR analysis have demonstrated the compatibility of the drug with the excipients of the formulations because the functional groups have remained the same without any chemical interaction. In summary, these results show that advanced pharmaceutical formulations have many benefits compared to traditional drug formulations due to the enhancement of the stability, performance, and compliance of the formulation. The use of characterization technologies helped analyze the formulation properties and provided confirmation about the successful development of pharmaceutical systems with the required physicochemical and thermal characteristics. In general, this research demonstrates the importance of advanced pharmaceutical formulation strategies that help overcome limitations of traditional formulations, especially regarding the solubility, bioavailability, and instability of drugs. Future research should concentrate on the development of methods for the industrial-scale production and long-term stability of advanced formulations along with their clinical validation and the development of artificial intelligence-assisted, personalized drug delivery, and stimuli-responsive pharmaceutical formulations.

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