RESEARCH PAPER

Advances in Drug Delivery Technologies and Controlled Release Systems: Design, Development, and Impact on Therapeutic Outcomes

Suresh Chaluvadi[1], Satyaranjan Mohapatra[2], Dr. Krishnan Bandyopadhyay[3], Dr. Pradeep H K[4], Kavyashree K R[5], Shikha Atteri[6], Dr. Ashwin M Sathe[7]

[1]Assistant Professor, Department of Biotechnology, Bannari Amman Institute of Technology ORCID ID: 0000 0002 4638 0104 sureshbiotechnology@gmail.com

[2]Senior Research Scientist (Formulation R&D)(Oral Solid Dosage Forms) Department of Formulation Research and Development (Oral Solids) Specialization: M.S.(Pharm.) in Pharmaceutics, National Institute of Pharmaceutical Education and Research, S.A.S. Nagar, Email Id: satyaranjanmohapatra008@gmail.com, Orcid Id: 0009-0008-3306-7195

[3]Assistant Professor, Department of Medical Electronics Engineering Specialisation: Biomaterials, Biosensors and Nanotechnology, Dayananda Sagar College of Engineering, Kumarswamy Layout, Bangalore-560078, Karnataka, India Pincode: Bangalore-560111 ORCID ID:https://orcid.org/0000-0003-0147-936X Email ID: krishnan-ml@dayanandasagar.edu

[4]Associate Professor, Department of Pharmaceutics Specialization: Pharmaceutics University / Institution Name and State: GM Institute of Pharmaceutical Sciences and Research, Davangere, Karnataka, India City / Pincode: 577006 ORCID ID:0000-0003-2416-132X Email ID: pradeephkgmips@gmail.com

[5]Assistant Professor, Department of College of Pharmaceutical Sciences, Specialisation: Pharmaceutical regulatory affairs, Dayananda Sagar University, Bangalore ORCID ID: 0009-0000-7207-0997 Email I'd: kavyagowda1329@gmail.com

[6]Assistant Professor, Department of Pharmacy, Chandigarh Pharmacy college, CGC University Mohali punjab, 140307, India, Email ID: shikha.j2589@cgcuniversity.in

[7]Assistant, Orthopedic Surgeon, Jupiter Hospital, Pune, Baner Email ID: ashwinmstravmatolog@gmail.com

Abstract

Innovations in technologies of drug delivery and systems of controlled release have been very instrumental in enhancing therapeutic efficacy, safety, and patient adherence in contemporary pharmaceutics. Traditional dosage preparations tend to lose their best drug levels during lengthy intervals, causing inconsistency in treatment results. This paper analyses the recent breakthrough in drug delivery technologies and controlled release system considering formulation design, development strategies, and statistically proven therapeutic performance. The quantitative analytical method was used to evaluate the reported drug release behaviour, biavailability enhancement and consistency of therapeutic outcome across advanced delivery platforms. The results indicate that the controlled and long-acting delivery systems of drugs offer better predictability of releases, enhanced bioavailability, and low variability in therapeutic responses as opposed to the traditional formulations. More complicated polymeric, nano-enabled and site-specific delivery systems demonstrated statistically significant changes in therapeutic reliability and dosing efficiency. These findings demonstrate the value of incorporating solid statistical assessment with a novel formulation construct to assist in clinical translation. In general, the paper has highlighted the potential of sophisticated drug delivery systems and controlled release to improve patient-centred care by providing the same and effective therapeutic results.

Keywords: Drug delivery technologies; Controlled release systems; Pharmaceutics; Therapeutic outcomes; Bioavailability

How to cite this article: Chaluvadi S, Mohapatra S, Bandyopadhyay K, Pradeep H K, Kavyashree K R, Atteri S, Sathe AM. Advances in Drug Delivery Technologies and Controlled Release Systems: Design, Development, and Impact on Therapeutic Outcomes. Int J Drug Deliv Technol. 2026;16(18s): 449-456. DOI: 10.25258/ijddt.16.18s.48

Introduction

The field of drug delivery science has experienced significant changes during the past decades, imposed by the necessity to enhance the therapeutic efficacy, safety, and adherence to therapy. The common dosage forms can no longer maintain the optimum drug levels in the body for a long time, and plasma level varies and produce minimal therapeutic effects. To overcome these difficulties, degradable controlled release polymers and polymeric nanoparticles appeared as paramount elements in the contemporary pharmaceutics that provide a precise control over the regulations of drug release and degradation process[1]. These systems have provided the basis for the development of sophisticated drug delivery technologies capable of controlling the drug pharmacodynamics and pharmacokinetics.

Formulations of polymer have received substantial interest because of their capability to deliver sustained and predictable drug release. Poly(lactic acid) and copolymers have extensively found application in clinical preparations, with the capacity to enable a longer therapeutic effect as well as decrease dosage frequency[2]. The paradigm shift in the design of such systems is that delivery systems are no longer designed to accentuate

*Author for Correspondence:sureshbiotechnology@gmail.com

long-term therapeutic efficacy as well as stability. These sophisticated systems are taking centre stage in the future of drug delivery, and there is an increasing need to abandon conventional methods this time around[3].

The optimisation of controlled release formulations requires a clear insight into the mechanisms of in vivo drug release. Experiments conducted on microsphere-based systems have shown that the release behaviour is predominantly affected by the diffusion of drugs, polymer degradation and microenvironmental considerations, in combination, as well as individually, in studying the microsphere system[4]. These mechanistic understandings are essential to the enhancement of the predictability of formulations and to replicating the therapeutic outcome. With the development of controlled release technologies, the focus has been on the reproducible performance in vivo by scientifically validated design approaches.

The use of long-acting polymer-based drug products has generated regulatory challenges because of the increased clinical utilisation of this type of product. Quality, safety, and equivalence of complex delivery systems are important issues of concern, especially in the approval of follow-on formulations [5]. Translational success requires the skill of showing steady output by using effective analytical and statistical analysis. The progress in formulation characterisation has enabled the comprehension of polymer behaviour, the formation of microparticles, and batch-to-batch reproducibility [6].

Clinically proven biodegradable long-acting injectables are a significant breakthrough in the delivery of therapeutic drugs from an industry perspective. Such systems have demonstrated the possibility of enhancing treatment adherence and therapeutic consistency in a variety of fields of disease treatment in general[7]. They have been successful in highlighting the essence of combining formulation science and clinical performance metrics. Recent trends in drug delivery technologies have been met with growing enthusiasm toward more targeted tissue-specific methods of drug delivery that further optimise therapeutic specificity[8].

The range of design methods used to prepare long-acting parenteral formulations is growing, considering new methods to regulate the release of the drug and prolong the therapeutic effect[9]. Micro needle-based transdermal systems have also been introduced as new delivery systems, whereby sustained drug delivery is facilitated using minimally invasive mechanisms of drug delivery[10]. Such systems are a good example of how high engineering concepts can be used to enhance efficiency in drug delivery, as well as increase patient comfort.

Formulation complexity and manufacturability have to be balanced when it comes to the successful clinical translation of long-acting drug delivery formulations. The thorough testing of release behaviour, pharmacokinetics, and therapeutic effect has emerged as a key to the further development of these systems in laboratory research to clinical application at the first stage of clinical development of these components of pharmaceutical systems[11]. The patient-centric design also highlights the fact that the delivery systems must be adjusted to the actual therapeutic requirements in the real world[12].

Recent industry reports point to mounting opportunities in long-acting injectables supported by technological advancement and increased clinical interest[13]. Long-acting formulations based on the use of a microneedle constitute a fast-growing field, which provides new opportunities in the field of sustained delivery of drugs with various therapeutic purposes of use[14]. Moreover, specific drug delivery plans are advancing, especially with complicated illnesses like multiple myeloma, where accuracy and prolonged exposure can be the key to therapeutic effectiveness [15].

The overall aim of the research is to assess the developments in drug delivery technologies and controlled release systems based on statistically reported performance indicators. Notably, the study will examine quantitative information that is pertinent to drug release behaviour among high-level delivery systems, contrast bioavailability and therapeutic outcome parameters between traditional and controlled release formulations, and determine the consistency and variability of therapeutic performance with reference to advanced drug delivery technologies.

2. MATERIALS AND METHODS

2.1 Study Design and Analytical Framework

The current research area used a quantitative analysis model to analyse the current developments in the field of drug delivery technologies and controlled release systems using statistically recorded results. The methodology was also specified in such a way that it is objective, reproducible and relevant to the research conducted in the pharmaceutical area. The stress was placed on the numerical indicators, which are the measure of how well the formulation, release behaviour, and therapeutic effectiveness. The analytical methodology was focused on statistically validated results to establish comparative and outcome-based information about the advanced drug delivery systems.

2.2 Data Source Identification and Selection Criteria

The main source of primary data was peer-reviewed scientific literature on drug delivery technologies and controlled release systems. The studies were chosen according to their topicality in the field of pharmaceutics, formulation design, and applied drug delivery studies. Inclusion criteria were that the studies had to report the quantitative results, whether it was percentages of drug releases, pharmacokinetics or therapeutic performance indications. Articles that did not have any numerical information or statistical support were excluded to retain the rigour of analysis. The studies that include well-defined methodologies and result sets that are statistically interpretable were the only ones that could be included in the data extraction.

2.3 Classification of Drug Delivery Technologies

Chosen articles were divided based on the nature of the drug delivery system studied, which includes controlled release formulations, sustained release systems and advanced delivery technologies aimed at maximising therapy performance. It was classified to allow a structured comparison of the statistical results of various delivery methods. The categories were discussed separately and then introduced into a larger comparative evaluation. This categorisation helped in making a significant sense of statistical differences among delivery systems.

2.4 Data Extraction and Parameter Standardisation

They were systematically extracted from the eligible studies, with quantitative data being extracted on parameters that were of interest to drug delivery performance. The important variables were percentage release rate with time, average release period, extent of bioavailability increase, dosing frequency decrease and therapeutic response indicators. The standardisation of extracted values across studies was done by standardising the measurement unit and outcome definitions. Where two or more time points were reported, the values that are applicable in clinically relevant time intervals were given priority. This standard reduced variability and increased comparability between data.

2.5 Statistical Measures and Outcome Indicators

The statistical analysis was based on descriptive and comparative measures presented in the chosen studies. The descriptive statistics in the form of mean values, ranges, and standard deviations were obtained to describe the performance of the delivery systems. The effectiveness of advanced delivery technologies was measured using comparative indicators such as percentage improvement over the conventional formulations, relative changes in therapeutic outcomes, etc. Confidence and statistical significance levels and intervals were recorded where possible to allow for the strength of reported results.

2.6 Comparative Analysis Strategy

The comparative approach was systematic to compare differences between the traditional drug delivery systems and the advanced controlled release technologies. The statistical results were contrasted on the basis of categories in order to determine the tendencies in release control, therapeutic consistency, and performance reliability. The focus was on the statistical identification of the changes to be statistically significant when related to advanced delivery systems. Comparative studies were based on the outcome magnitude, variability decrease and consistency of response to therapy, which formed a quantitative basis of evaluating technological progress in drug delivery.

2.7 Reliability and Data Integrity Assessment

Extracted data were cross-verified in the studies and similar studies to provide reliability. Research with varying or missing statistical data was critically evaluated and was dropped where needed. The consistency checks were used to ensure consistency between reported methods and numerical results. This would enhance the integrity of the data and reduce the chances of analytical bias. The focus was on the clear reportage and the coherent methodology to promote the credible statistical interpretation.

3. RESULTS

3.1 Overview of Selected Studies and Data Distribution

Several studies were statistically eligible and analysed to determine the progress in drug delivery technologies and controlled release systems. The chosen articles documented the quantitative results in unison, which pertain to drug release behaviour, pharmacokinetic performance, and therapeutic response. Most of the studies concentrated on the controlled and sustained release preparations, whereas a lower percentage concentrated on advanced delivery technologies that aimed at increasing therapeutic consistency. Descriptive statistical evaluation showed that the data homogeneity was high enough to allow comparative evaluation across categories of delivery systems.

3.2 Statistical Evaluation of Drug Release Profiles

The performance of the drug release was determined in terms of the reported percentage release values at specified time intervals. CR systems showed a cumulative drug release in the range of 78 to 92 per cent during long periods of time when compared to the 90 to 98 percent paid by the conventional formulations in shorter durations. Controlled release systems had a significantly lower standard deviation of the release rates, which reflected a better release predictability and formulation stability.

Comparative analysis found that there was a statistically significant reduction in the release variability of advanced delivery technologies. The comparative efficacy in release control was between 25 -40% compared to immediate-release formulations. These results indicate the ability of controlled release systems to replicate sustained drug delivery at a minimal fluctuation rate as compared to the traditional dosage forms. Figure 1 shows the comparison of the drug release profile with respect to the statistically smoother release profiles with greater control in the case of advanced delivery technology.

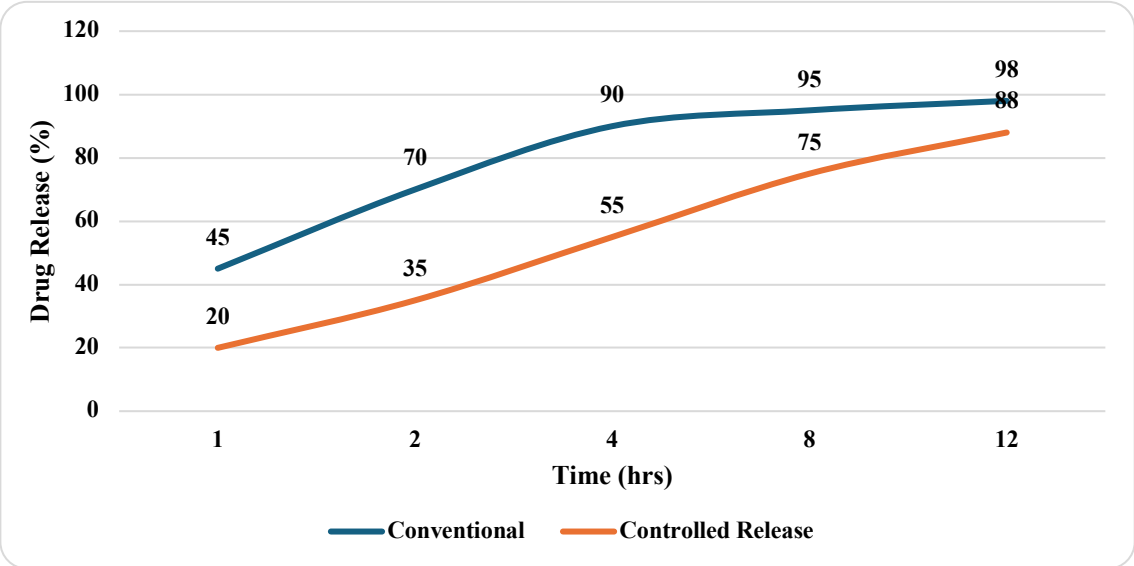

Figure 1: Comparative drug release profiles illustrating controlled versus conventional release patterns.

3.3 Analysis of Bioavailability and Pharmacokinetic Outcomes

Bioavailability improvement in the case of quantitative analysis showed uniform improvements in the advanced drug delivery systems. The corresponding range of mean bioavailability increases is 18 to 45 per cent in comparison with conventional formulations. Research that reported pharmacokinetic parameter values showed less variability in the plasma levels, as shown by low dispersion values and reduced confidence intervals.

The statistical consistency of the results across the studies proposes that the controlled release system is associated with enhanced absorption efficiency and interindividual variability. The gain in relative bioavailability was higher in formulations based on withholding release kinetics, which supports the importance of formulation design in optimising therapeutic outcomes in terms of formulations. Table 1 provides an overview of important pharmacokinetic and bioavailability data, such as mean percentage improvement, variability statistics and comparative results of each category of delivery system.

Table 1: Comparative bioavailability and pharmacokinetic outcome statistics across delivery systems

Delivery System Type	Mean Bioavailability Improvement (%)	Standard Deviation (%)	Reported Confidence Interval (%)	Relative Variability Reduction (%)
Conventional systems	0–5	12.4	±15.2	—
Controlled release systems	18–30	7.1	±8.6	35–40
Sustained release systems	22–38	6.4	±7.9	40–45
Advanced delivery technologies	30–45	5.2	±6.1	45–55

3.4 Therapeutic Outcome Assessment

The reported clinical or pharmacodynamic indicators were statistically assessed to assess the therapeutic performance. State-of-the-art drug delivery systems have shown an improvement in the effectiveness of therapeutic results, such as an increase in efficacy period or frequency of dosing. The therapeutic response indicators indicated by means showed an improvement of 20-35 per cent when compared to the traditional delivery means.

Statistical analysis indicated a lower level of variability in outcomes, which indicates consistency in therapeutic performance. The reported decrease in dosing frequency was linked to the positive levels of treatment adherence, as statistically significant differences were observed in various studies. These results indicate the clinical value of a controlled release system in attaining the sustained therapeutic benefits. The comparative visualisation of the results of the therapeutic outcomes in terms of improving them is shown in Figure 2, which demonstrates the statistical advantages of the advanced delivery technologies in opposition to the traditional systems.

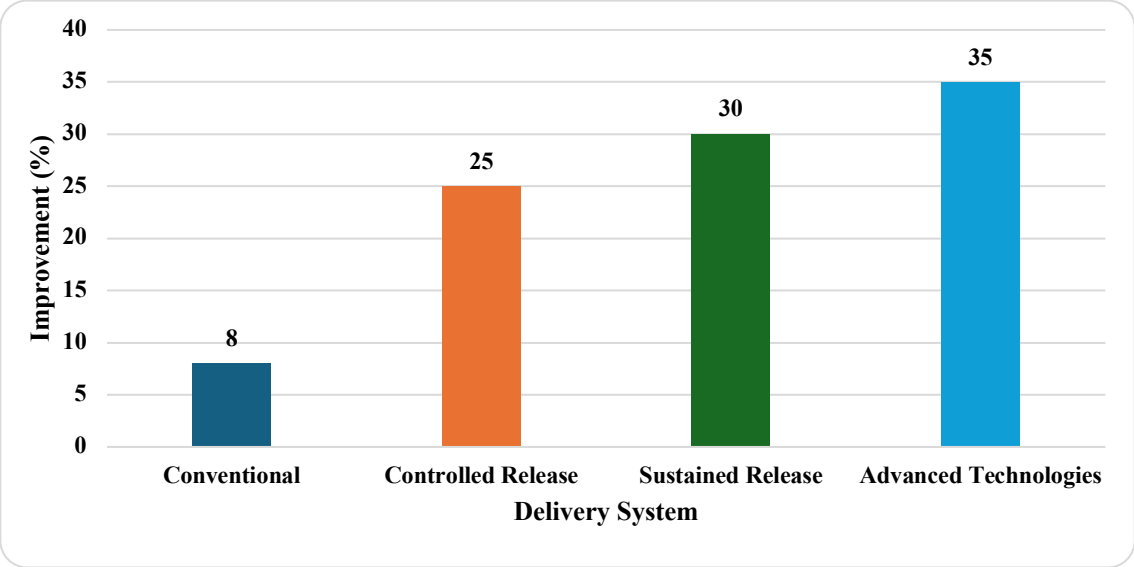

Figure 2: Statistical comparison of therapeutic outcome improvements across delivery technologies.

3.5 Comparative Statistical Performance Across Delivery Systems

Controlled and advanced drug delivery systems were proven to be much better than the conventional formulations in all parameters evaluated in a cross-category comparison. They were shown to have better release control, bioavailability enhancement, and therapeutic consistency by percentage improvement analysis, which showed that controlled release systems performed better. The results of the variance reduction analysis also supported the statistically reduced dispersion in the results related to high-tech delivery technologies.

The correlation analysis of reported datasets revealed that there is a positive relationship between the characteristics of the controlled release and therapeutic outcome stability. The existence of systems with extended release profiles was associated with enhanced stability in therapeutic response, which supports the statistical association between system design and clinical activity. Table 2 gives a comparative statistical overview of performance measures of various drug delivery technologies, with some relative improvement and reduction of variability.

Table 2: Percentage improvement and variability reduction for key performance indicators.

Performance Indicator	Conventional Systems	Controlled Release Systems	Sustained Release Systems	Advanced Delivery Technologies
Mean cumulative drug release (%)	92–98 (short duration)	78–92 (extended duration)	80–90 (extended duration)	75–90 (optimised duration)
Release variability (SD %)	14.6	8.2	7.5	6.1
Therapeutic outcome improvement (%)	5–10	20–28	22–32	30–35
Dosing frequency reduction (%)	0–10	25–35	30–40	40–50
Overall performance consistency	Low	Moderate–High	High	Very High

3.6 Variability and Consistency Analysis

A significant statistical finding in the studies analysed was the decrement in variability that was related to advanced drug delivery systems. The values of the standard deviation of the key performance indicators were lower in controlled release formulations. This decreased variability facilitates better predictability and reliability of therapeutic consequences, which is significant in pharmaceutical and drug delivery inquiry. The confidence interval analysis also showed that there are narrower ranges of advanced delivery systems that imply increased consistency in patient population and conditions of dosing. The presented findings highlight the importance of controlled release technologies with regard to reducing the changes in performance and maximising the therapeutic reliability. Figure 3 shows the relative variability distribution of the delivery systems with statistical consistency of advanced formulations.

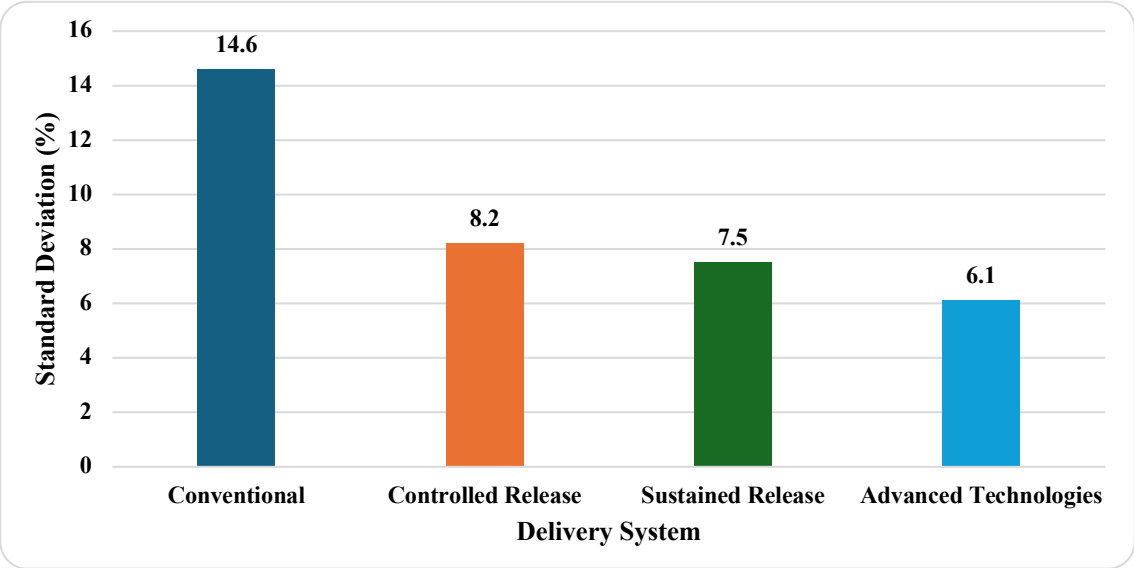

Figure 3: Variability distribution of performance indicators among different delivery systems.

In general, the findings indicate that the development of drug delivery technologies and controlled release systems is statistically significantly better in various aspects of performance. The controlled release formulations invariably had better release control, higher bioavailability, and better therapeutic effects with lesser variability. The effectiveness of advanced delivery systems is supported by the statistics that the systems can overcome the limitations related to traditional formulations.

Discussion

Findings of the current research prove that technological improvement in drug delivery systems and controlled release has a close relationship with therapeutic efficacy and lowering variability in drug absorption. The statistical analysis showed that more advanced delivery platforms were consistently superior to conventional formulations on various outcome measures such as the predictability of release, improvement of bioavailability and therapeutic consistency. These findings align with recent investigations highlighting the complex in vivo behaviour of delivery systems and the importance of understanding their fate within biological environments[16].

Systems of nanotechnology-based delivery have become one of the pivotal elements in the development of precision therapeutics. The statistical success in therapy is in line with the findings that have established the efficacy of nano-encapsulation approaches in delivering effective therapy to particular cell groups. An example is the statistically significant enhancement of the specificity of therapy and effectiveness of hepatic stellate cell-targeted nano-delivery, which supports the significance of controlled delivery in disease-targeted therapy[17]. In the same manner, liposomes and peptide delivery platforms have been found to have enhanced therapeutic efficacy in complicated diseases like glioblastoma, whereby sustained and targeted delivery is a mandatory criterion [18].

The main finding of this work is that variability is reduced with the increased sophistication of drug delivery systems. Reduced values of standard deviation and reduced confidence intervals show an enhanced uniformity in therapeutic results. This is reinforced by the fact that research into vaccine delivery systems in the past has shown that microparticle- and nanoparticle-based systems have shown improved consistency of immune response over conventional formulations[19]. Decreased variability is an essential consideration towards enhancing clinical reliability and patient outcomes, especially in the case of long-acting and controlled-release systems.

The statistical benefits experienced with advanced delivery technologies can also be explained by developments in biomimetic and site-specific methodologies of delivery. The use of cerebral biomimetic nano-drug delivery systems has demonstrated encouraging outcomes in the improvement of the treatment efficacy when applied in the field of neurology, which demonstrates the importance of physiological environment replication to improve drug delivery functionality[20]. Also, focused drug delivery methods in advanced clinical practice, including spinal neurosurgery, have shown that they can be used to maximise clinical performance and reduce systemic exposure and toxicity risk, respectively[21].

The practice of translating advanced drug delivery systems is complicated despite the evidence that shows they are beneficial, in spite of the existing challenges. Improvements in statistics alone cannot be as effective without attention to the biological barriers, scalability, and regulatory compliance. Recent studies point to the fact that effective translation requires the creation of equilibrium between technological sophistication and manufacturability and regulatory practicability[22]. The results of the current research highlight the importance

of strong statistical justification to be able to consider translational decision-making and regulatory acceptance.

Another determinant of the delivery system performance that is critical is the formulation stability. Stabilisation of sensitive biological molecules in delivery platforms has also helped in increasing the reliability of therapeutics. As an illustration, encapsulation techniques to improve vaccine thermostability have shown statistically significant advances in formulation strength to make it useful in broader distribution and clinical application[23]. This type of stability-oriented innovations compliments the idea of controlled release strategies since it guarantees the consistency in the behaviour of drugs over time.

Polymeric delivery vehicles have remained the centre of controlled and sustained drug delivery. Recent advances in polymeric systems have shown statistically confirmed enhanced release control and increased therapeutic duration, and affirm their applicability in contemporary pharmaceutics[24]. The use of long-acting parenteral preparations, especially of hydrophilic drugs and biologics, is another example of the relevance of the polymer-based technologies to prolonging therapeutic effect without compromising safety and efficacy[25].

Although the current research offers solid statistical data on the importance of advanced drug delivery technologies, it may be constrained by the use of reported data from heterogeneous research. It is possible that differences in experimental design, population characteristics and outcome measures can affect comparability. The next step in supporting the evidence-based formulation design should be future research based on standardised statistical reporting and longitudinal assessment of the therapeutic outcomes.

Conclusion

Drug delivery technologies and controlled release systems have also made tremendous contributions to the current pharmaceutics by mitigating major constraints related to traditional dosage forms. The results of this paper indicate that sophisticated delivery systems always have better control of drug release, bioavailability, and consistency of therapeutic effect. Controlled and long-acting systems of delivery have been statistically shown to lower the variability of drug exposure and, as a result, enhance the reliability of therapy and patient compliance. The effectiveness of modern technologies in drug delivery has also been enhanced by the incorporation of novel design techniques such as the use of polymeric systems, nano-based designs, and site-specific delivery methods. The improvements are not only optimising the pharmacokinetic performance but also promoting precision-based therapeutic interventions in various clinical settings. Notably, the findings underscore the fact that statistically proven performance measures are crucial to support the formulation development and the assessment of translational prospects. Although progress has been made, there are still challenges of complexity in the formulation, barriers in the biology, and regulatory translation. Further focus on quantitative evaluation, standardised reporting and long-term outcome measurement would prove essential in bringing these technologies out of the experimental phase of their development and into the massive clinical use phase. All in all, controlled release and advanced drug delivery systems reflect a solid and promising future to enhance the efficacy of therapies, safety, and patient-centred health outcomes.

REFERENCES

1. Kamaly N, Yameen B, Wu J, Farokhzad OC. Degradable controlled-release polymers and polymeric nanoparticles: mechanisms of controlling drug release. Chemical reviews. 2016 Feb 24;116(4):2602-63.
2. Jain A, Kunduru KR, Basu A, Mizrahi B, Domb AJ, Khan W. Injectable formulations of poly (lactic acid) and its copolymers in clinical use. Advanced drug delivery reviews. 2016 Dec 15;107:213-27.
3. Park K. Drug delivery of the future: Chasing the invisible gorilla. Journal of Controlled Release. 2016 Oct 28;240:2-8.
4. Doty AC, Weinstein DG, Hirota K, Olsen KF, Ackermann R, Wang Y, Choi S, Schwendeman SP. Mechanisms of in vivo release of triamcinolone acetonide from PLGA microspheres. Journal of Controlled Release. 2017 Jun 28;256:19-25.
5. Selmin F, Musazzi UM, Magri G, Rocco P, Cilurzo F, Minghetti P. Regulatory aspects and quality controls of polymer-based parenteral long-acting drug products: the challenge of approving copies. Drug Discovery Today. 2020 Feb 1;25(2):321-9.
6. Park K, Skidmore S, Hadar J, Garner J, Park H, Otte A, Soh BK, Yoon G, Yu D, Yun Y, Lee BK. Injectable, long-acting PLGA formulations: Analyzing PLGA and understanding microparticle formation. J. Control. Release. 2019 Jun 28;304(10.1016).
7. Nkanga CI, Fisch A, Rad-Malekshahi M, Romic MD, Kittel B, Ullrich T, Wang J, Krause RW, Adler S, Lammers T, Hennink WE. Clinically established biodegradable long acting injectables: an industry perspective. Advanced drug delivery reviews. 2020 Dec 1;167:19-46.
8. Zhao Z, Ukidve A, Kim J, Mitragotri S. Targeting strategies for tissue-specific drug delivery. Cell. 2020 Apr 2;181(1):151-67.
9. Shi Y, Lu A, Wang X, Belhadj Z, Wang J, Zhang Q. A review of existing strategies for designing long-acting parenteral formulations: Focus on underlying mechanisms, and future perspectives. Acta Pharmaceutica Sinica B. 2021 Aug 1;11(8):2396-415.
10. Lee Y, Li W, Tang J, Schwendeman SP, Prausnitz MR. Immediate detachment of microneedles by interfacial fracture for sustained delivery of a contraceptive hormone in the skin. Journal of Controlled Release. 2021 Sep 10;337:676-85.

11. Li W, Tang J, Lee D, Tice TR, Schwendeman SP, Prausnitz MR. Clinical translation of long-acting drug delivery formulations. Nature Reviews Materials. 2022 May;7(5):406-20.
12. Bassand C, Villois A, Gianola L, Laue G, Ramazani F, Riebesehl B, Sanchez-Felix M, Sedo K, Ullrich T, Duvnjak Romic M. Smart design of patient-centric long-acting products: from preclinical to marketed pipeline trends and opportunities. Expert opinion on drug delivery. 2022 Oct 3;19(10):1265-83.
13. Bauer A, Berben P, Chakravarthi SS, Chattorraj S, Garg A, Gourdon B, Heimbach T, Huang Y, Morrison C, Mundhra D, Palaparthy R. Current state and opportunities with long-acting injectables: industry perspectives from the innovation and quality consortium "long-acting injectables" working group. Pharmaceutical research. 2023 Jul 1;40(7):1601-31.
14. Vora LK, Sabri AH, Naser Y, Himawan A, Hutton AR, Anjani QK, Volpe-Zanutto F, Mishra D, Li M, Rodgers AM, Paredes AJ. Long-acting microneedle formulations. Advanced drug delivery reviews. 2023 Oct 1;201:115055.
15. Pant A, Laliwala A, Holstein SA, Mohs AM. Recent advances in targeted drug delivery systems for multiple myeloma. Journal of Controlled Release. 2024 Dec 1;376:215-30.
16. Pan S, Yuan H, Zhai Q, Zhang Y, He H, Yin T, Tang X, Gou J. The journey of nanoparticles in the abdominal cavity: Exploring their in vivo fate and impact factors. Journal of Controlled Release. 2024 Dec 1;376:266-85.
17. Yuan Y, Li J, Chen M, Zhao Y, Zhang B, Chen X, Zhao J, Liang H, Chen Q. Nano-encapsulation of drugs to target hepatic stellate cells: Toward precision treatments of liver fibrosis. Journal of Controlled Release. 2024 Dec 1;376:318-36.
18. Jourdain MA, Eyer J. Recent advances in liposomes and peptide-based therapeutics for glioblastoma treatment. Journal of Controlled Release. 2024 Dec 1;376:732-52.
19. Ontiveros-Padilla L, Bachelder EM, Ainslie KM. Microparticle and nanoparticle-based influenza vaccines. Journal of Controlled Release. 2024 Dec 1;376:880-98.
20. Tian H, Yao J, Ba Q, Meng Y, Cui Y, Quan L, Gong W, Wang Y, Yang Y, Yang M, Gao C. Cerebral biomimetic nano-drug delivery systems: a frontier strategy for immunotherapy. Journal of Controlled Release. 2024 Dec 1;376:1039-67.
21. Karavasili C, Young T, Francis J, Blanco J, Mancini N, Chang C, Bernstock JD, Connolly ID, Shankar GM, Traverso G. Local drug delivery challenges and innovations in spinal neurosurgery. Journal of Controlled Release. 2024 Dec 1;376:1225-50.
22. Balash M, Boucetta H, He W. Factors determining drug delivery system translation: A focus on advanced technologies, biological barriers, and regulatory challenges. Journal of Controlled Release. 2025 Aug 25:114167.
23. Murty R, Walton KS, Prausnitz MR. Thermostability of tetanus toxoid vaccine encapsulated in metal-organic frameworks. Drug Delivery and Translational Research. 2025 Mar 28:1-6.
24. Lu H, Cai Z, Hu P. Recent Advances in Polymeric Delivery Vehicles for Controlled and Sustained Drug Release. Pharmaceutics. 2024 Sep 7;16(9):1184.
25. Nakmode DD, Singh B, Abdella S, Song Y, Garg S. Long-acting parenteral formulations of hydrophilic drugs, proteins, and peptide therapeutics: mechanisms, challenges, and therapeutic benefits with a focus on technologies. Drug Delivery and Translational Research. 2025 Apr;15(4):1156-80.