NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES (NIJSES)

Volume 6 Issue 3 Page 14-20, 2025

©NIJSES PUBLICATIONS
Open Access

ONLINE ISSN:2992-5819
PRINT ISSN:2992-6149

https://doi.org/10.59298/NIJSES/2025/63.1420

Biopharmaceutical Engineering: Innovations in Drug Development

Awafung Emmanuel

Electronics and Biomedical Engineering, Kampala International University Uganda

Email: awafungadie@gmail.com

ABSTRACT

Biopharmaceutical engineering represents a revolutionary frontier in modern medicine, enabling the development of complex biological drugs through advanced biotechnology. Unlike traditional small-molecule drugs, biopharmaceuticals, including monoclonal antibodies, peptides, recombinant proteins, and gene therapies, are produced in living systems, offering highly specific and effective treatments for chronic and previously untreatable diseases. This paper examines the historical evolution of drug development, contrasts biopharmaceuticals with traditional pharmaceuticals, and highlights the key technologies transforming the sector, including high-throughput screening, fragment-based drug discovery, and Quality by Design (QbD). It delves into the intricacies of formulation, delivery, and quality control, and critically assesses challenges such as sustainability, regulatory compliance, and workforce gaps. Drawing from case studies such as Rituxan and bispecific monoclonal antibodies, the paper demonstrates how innovation and engineering strategies have shortened development cycles and improved drug efficacy. Emerging trends and sustainability frameworks are also examined to propose a roadmap for the future of biopharmaceutical development. Ultimately, the integration of scientific innovation, robust engineering, and sustainable practices is pivotal to shaping the next era of drug discovery and delivery.

Keywords: Biopharmaceuticals, Drug Development, Monoclonal Antibodies, Biosimilars, Recombinant Proteins, Biotechnology, Quality by Design (QbD), Drug Formulation.

INTRODUCTION

Biopharmaceuticals are primarily therapeutic recombinant proteins produced through biotechnological methods. Living cells possess the ability to secrete complex proteins into the culture medium efficiently, unlike chemical synthesis, which struggles to create proteins with the desired properties at low costs. With advancements in genetic engineering and animal cell culture, biopharmaceuticals have become more sophisticated, leading to various products from the same gene, each differing in glycosylation patterns and structures. Once obtained from living cells, the proteins require concentration and purification from the medium, followed by formulation and stabilization for patient supply, termed the bioprocessing stage. Drug development is expensive and complex, with only 4% of new entities gaining approval, taking about 10-16 years. In the next 5 to 10 years, it is anticipated that up to 50% of drugs in development will include biopharmaceuticals, such as proteins, peptides, antibodies, and tools like siRNA and DNA vaccines. There is no single "best" drug, as a gene product can yield a specific protein via animal tissue extraction or recombinant DNA techniques. Variability among products from different manufacturers leads to distinctions between reference medicines and biosimilars due to manufacturing differences. The first biosimilar biopharmaceutical was approved in Europe in 2006, and its low cost has significantly increased its adoption. Additionally, two gene therapy products have received licenses in Europe for human therapeutic use [1, 2].

Historical Overview of Drug Development

Introducing a new chemical entity (NCE) into the pharmaceutical market is a time-consuming process, typically taking over 15 years from drug discovery to market. This journey involves numerous interconnected steps, as pharmaceuticals are developed and commercialized as a business. Pharmaceutical companies act as hubs of scientific expertise, employing trained biopharmaceutical engineers to prioritize drug development and research investment. Historically, drugs were basic biological materials that now require purification or characterization for proper use. Separation and purification techniques originated centuries ago and have evolved significantly. The last century has seen biochemistry and pharmacology emerge as distinct scientific fields, enhancing our understanding of drug-target interactions and development pathways. Modern biotechnology and biopharmaceutical engineering have advanced drug development, merging classical chemical processes with biocatalytic advancements. A renewed focus on biocatalysis and investment in this area is propelling progress in the pharmaceutical sector. Pharmaceutical bioengineering plays a crucial role in recovering small molecules, peptides, and genes from production systems. The past decade has marked significant updates in the pharmaceutical industry, involving previously laymanistic scientists in development and research efforts [3, 4].

Biopharmaceuticals vs. Traditional Pharmaceuticals

A biopharmaceutical is a drug produced via biological or "biotech" processes, distinguishing it from traditional pharmaceuticals based primarily on its manufacturing process and structure. A drug that is an organic small molecule manufactured biotechnologically is not classified as a biopharmaceutical, while an IgG1 monoclonal antibody synthesized chemically is. Biopharmaceuticals, irrespective of being small or large molecules, are defined by being macromolecules made through biotech processes. Structure-wise, the classification depends on molecular weight, with small molecules under 1000 Da categorized as traditional pharmaceuticals regardless of biotech methods, while large molecules exceeding 5000 Da are. To further specify biopharmaceuticals, three types can be identified: (1) macromolecule (over 1000 Da), (2) biopharmaceutical (more than 5000 Da), and (3) biologic, which strictly comprises active ingredients produced biologically. Biopharmaceuticals can also be differentiated from traditional pharmaceuticals based on proprietary technology or subclasses, including small interfering RNA (siRNA) and monoclonal antibodies. The pharmaceutical industry faces a pivotal moment in the USA and Europe, balancing between enhancing current science and exploring new drug discovery paradigms, particularly for unmet medical needs like depression, obesity, and chronic pain. Biopharmaceutical development is viewed as a major share of the new drug pipeline, while traditional pharmaceuticals often focus on improvements of existing drugs. This trend is supported by an expected 20% CAGR for biopharmaceutical products, driven by investments in monoclonal antibodies and protein products over the next decade, contrasting with a decline for traditional small-molecule products [5, 6].

Key Technologies in Biopharmaceutical Engineering

Biopharmaceutical engineering has evolved from the biomedical, biotechnology, and pharmaceutical sectors. Advanced high-throughput screening and sensitive in vitro assays have created an information-rich environment for drug discovery. Breakthroughs in biology and supramolecular chemistry have increased potential drug targets and improved drug properties. However, preclinical and clinical drug design rates stagnated over the past decade, leading to productivity declines. This review outlines new biopharmaceutical engineering technologies, focusing on early development, preclinical formulation, evaluation, and clinical formulation of investigational new drugs, complementing high-throughput screening. Enhanced understanding of drug transport, stability, and immunoevaluability has reduced preclinical formulation attrition rates. Despite the promise of biopharmaceuticals, which were once seen as niche solutions for severe diseases, they are now critical in blockbuster drug development. Nonetheless, drug development rates for preclinical and clinical candidates have stagnated, with design productivity declining significantly since 2002, despite increased investments in drug discovery. This review aims to contextualize these engineering technologies within the broader scope of drug innovation and identify their roles in rational drug design and candidate optimization. [7, 8].

The Drug Development Process

The modern biopharmaceutical development process usually involves the steps of target identification, high-throughput screening to identify drug leads, preclinical development, clinical development, registration, and launch. This development process comes after a prior fundamental understanding of the disease to determine a drugable target. The development process generally takes about 10-20 years and costs tens of billions of dollars. This is where the bottleneck for the bioindustry and biomedical communities lies today. The structure of current drugs is mostly small organic compounds (< 1000Da)

discovered through high-throughput screening with a fixed target structure. These drugs are limited in increased potency and target selectivity due to the rule-of-five. The non-specific interactions of drug candidates in drug discovery usually evolve into further toxicity and side effects. These low target selectivity drug candidates also tend to have significantly reduced therapeutic index for the safe and effective dose ranges. Currently, there is an interest in developing mid-sized macrocyclic compounds (1000 - 3000Da), nano-scaled biomolecules (e.g., peptides, proteins, DNA, RNA) as new modalities against the previously undrugable target space as a significant advancement in biopharmaceutical discovery from the chemistry perspective. Experimental high-throughput and complex screening at the discovery stage results in high drug lead/target candidates for inefficient IDRS processing. While a large number of drug leads fail to demonstrate adequate activity or targeted specificity throughout development, it is also difficult to narrow the leads down to the desired targets, as the same or similar drug leads generally can bind to multiple targets or moieties. Fragment-based drug discovery is a promising approach to alleviate the limitations of the common small-molecule drugs. The target identification and SAR exploration using small fragments (molecular weight < 300) is generally low in potency and selectivity. As the discovery philosophy will diverge from the elaboration on single drug lead space (small molecules and known binding orientation) towards the diversification into larger chemical space in multiple drug lead series in parallel (macrocyclic compounds, biomolecules, substrate mimetic microorganisms, etc.) with probable higher affinity/probability units [9, 10].

Formulation and Delivery Systems

One of the biggest challenges in biopharmaceutical development is to formulate a new drug candidate that has a sufficient physical stability under realistic and accelerated storage conditions and has the maximum solubility, bioavailability, and transport capacity. From a physical point of view, the major reasons for the formulation failure of biopharmaceuticals are instability at elevated or decreased pH or temperature conditions, as well as precipitation or aggregation phenomena when changing the formulation in a solid state. For biopharmaceuticals with a high solubility but fast degradation, the storage period has to be maximized by adjusting the pH and the kind and concentration of stabilizing excipients. If biopharmaceuticals are in a solid state, matrix formation has to be ensured during the drying process, which extends the protein domain of cross-interaction and results in reduced hydration and maximum glass transition temperature. This allows the storage of biopharmaceuticals over years at European dimensions, even above kT. Nevertheless, formulation development requires the analysis of multiple parameters, some of which depend on each other. Most of these investigations are purely given from an empirical point of view. Highly informative screening systems to better understand and predict the properties of biopharmaceutical formulation candidates and provide a straightforward interpretation of stability screening efficiency. High-throughput screening devices allow measuring thermal events in various biopharmaceutical formulation candidates at EC and realistic, even at elevated and very low temperatures, in a holistic way. In parallel, novel reading approaches allow the biopharmaceutical solid state to be characterized with an unprecedented resolution and speed. The application of these screening technologies has shown the potential to avoid the pitfalls of formulation processes. The combination with advanced multi-component systems allows studying the interplay of formulation characteristics. Comprehensive stability screening, characterization, and understanding enable an experimental approach to formulate more soluble and more stable biopharmaceutical drugs [11, 12].

Quality Control and Assurance in Biopharmaceuticals

Biopharmaceuticals are crucial in modern medicine, offering effective treatments, yet their complex structures make analysis and manufacturing challenging compared to small-molecule drugs. Inconsistencies in production can lead to unsafe drugs and serious risks for patients. Regulatory bodies propose various tools to ensure consistency and safety throughout the biopharmaceutical lifecycle. The intent is to analyze the risks associated with unscientific manufacturing practices, impacting product safety and quality. The regulation emphasizes “Process understanding” to assure safety and quality influenced by bioprocesses. Quality by Design (QbD) is a contemporary technique used for quality control in biopharmaceuticals. These products are primarily created using cellular systems that can produce variable outputs due to unknown biosafety and quality parameters, resulting in non-compliant, ineffective products that may harm patients. QbD systematically addresses bio-therapeutic biology and bioprocesses to ensure compliance with regulatory standards for valuable molecular entities. By enhancing understanding and controlling quality assessments in bioprocess steps, QbD supports steady improvements in critical quality attributes (CQA), product safety, and quality assurance within the

biopharmaceutical sector. Assessing bioprocess robustness involves using a bio-assay model developed through statistical methods for better process control. With diverse applications in drug development and post-approval manufacturing, QbD is essential for producing safer, effective, compliant, and affordable biopharmaceuticals, ultimately benefiting public health [13, 14].

Challenges in Biopharmaceutical Development

The growth of the biopharmaceutical industry has prompted concerns about the sustainability of biopharmaceutical manufacturing processes and potential adverse impacts on human health and the environment. The industry faces challenges related to constraints around process automation, retrofitting of existing plants, and the requirement for skilled personnel. Drug developers often focus only on the therapeutic and biosafety profile of the product being developed while ignoring the overall sustainability of the drug. Sustainability considerations need to be integrated into early biopharmaceutical process development. Traditionally, industry sustainability performance has focused on environmental aspects, with economic and social dimensions largely neglected. The industry also faces an aging workforce, necessitating workforce succession planning and retention of knowledge within the organization. Recent trends towards reducing workforce levels in a highly competitive market are increasing these concerns. Furthermore, it is not always clear what information should be shared publicly – some data must remain confidential to protect commercial interests. Barriers remain around the ability and willingness of firms to share information and collaborate. Even with the adoption of more sustainable practices, the industry needs to remain vigilant to the emergence of new challenges. New discussions on policies are needed to provide educational benchmarks to ensure systemic processing can be integrated into a firm's standard product review processes. Input from multiple disciplines will be necessary to clarify and determine benchmarks for sustainable best practices in manufacturing. Moreover, sustainability is expected to be at the core of technological innovations throughout the biopharmaceutical sector. Such a holistic approach would allow the industry to compete effectively and safeguard patient safety and public health while reducing unwanted environmental impacts. The efforts of individual companies or departments to improve sustainability, such as through greener processes or equipment, should be paralleled by an industry-wide commitment to sustainability [15, 16].

Emerging Trends in Biopharmaceuticals

Researchers and investors are increasingly focused on biopharmaceutical advances for cancer, neurological diseases, allergy, hepatitis B, and higher-risk conditions. Prioritizing these advances is vital, as the study of genomes and immune systems in higher organisms flourishes. Current Cartesian methods from physics and mathematics fall short in revealing biologics' properties and functions. Thus, biopharmaceutical R&D must emphasize life materials from biology and chemistry instead of physics and mathematics. The manufacturing of biologics requires controllable, transparent, reliable, and modular infrastructures that facilitate self-assembly and adjustment. Brain drain poses challenges for research and infrastructure advancements; however, raising average scientific salaries in China could mitigate this issue. English teaching that is culturally aware and language-specific might enhance brain reactivation. Furthermore, sustainable operations in the biopharmaceutical sector are essential for competitive advantage. Despite identifying some sustainability challenges, there remains limited understanding of the sector's sustainability performance and the knowledge needed for developing effective business models for continuous improvement. This paper comprehensively assessed various sustainability factors within the sector, pinpointing barriers and opportunities for enhancing sustainability performance. A business excellence framework was created to assist biopharmaceutical leaders in formulating a roadmap addressing the identified challenges. This framework consists of three main components: a composite sustainability assessment tool, business operational models, and performance improvement pathways. Future research is suggested to further develop the framework, including a quantitative sustainability assessment tool and guidelines for implementing these models while evaluating and improving sustainability performance [17, 18].

Case Studies of Successful Biopharmaceuticals

A leading company for monoclonal therapeutics, Genentech was responsible for the first engineering project of a biopharmaceutical drug, Rituxan, which was marketed by Roche in 1997 and developed as a treatment for non-Hodgkin's lymphoma and chronic lymphocytic leukaemia. Rituxan is a humanized IgG1k antibody that was developed against CD20, an antigen selectively expressed in B-lymphocytic cells. Rituxan was cloned using hybridoma technology. The bioreactor was the first of its kind to obtain biologics at a large scale (10 kL). Filtration use was encouraged for upfront clarification of the harvest. The central concentration step utilized a proprietary membrane protein-A column process. This was

followed by polishing steps using a proprietary cation exchange column and a second anion-exchange column. All these proprietary processes performed on proprietary equipment from the same supplier implied a very high annual throughput, with the first plant yielding 1200 doses/month. After over twenty years of successful development and commercialization of monoclonal antibody therapeutics, a spinoff team of a major biotech company was given the task to develop, manufacture, and commercialize a bispecific antibody platform technology. These bispecific mAbs are a higher-order structure of complex and will pose higher challenges in the development, manufacturing, characterization, and regulatory compliance than the unispecific mAbs. Understanding of the mechanisms of action of these bispecific mAbs was critical to guide the development process. The team was built up for process development. Existing core processes for the established mAb assets were used as the starting point. However, due to the bispecific nature of these new drugs, validation of product quality and process consistency was much more stringent. Also, due to the speed to market and the highly competitive landscape, the process development cycle time from a bioreactor scale of 200 L to 15,000 L was planned for less than 18 months [19-23].

Future Directions in Biopharmaceutical Engineering

Biopharmaceutical engineering comprises innovative research and development in drug discovery and modeling of biopharmaceutical processes, including upstream processes, downstream processes and formulation technologies development, design space characterization and control, validation, regulatory considerations, and case studies. Decentralized drug formulation and biosimilar drug development are emphasized in the case studies. This paper discusses the innovation in biopharmaceutical engineering, including the innovation in drug discovery, the current biopharmaceutical engineering technologies, future-oriented biopharmaceutical process developments, and the need for a robust chemical and biopharmaceutical industry. Recent technological advancements in biopharmaceutical engineering will shed light on the manufacturing of protein-related biomolecules, including mAbs, ADCs, fusion proteins, virus-like particles, peptides, viruses, and gene drugs. Biopharmaceutical posttranslational modification, structural characterization, impurity monitoring, quality control strategies, and estimation of protein conformation, aggregation, and stability are reviewed. Looking ahead, expanded adoption and aggregation of advances made in the area of chem informatics and AI-based drug design discovery and modeling requires a fresh look at approaches taken in developing the now decades-old. Investments in facilities to conduct the development and manufacturing of biopharmaceuticals, a timeline that favors development and integration of an R&D biopharmaceutical industry, and the design of biopharmaceutical engineering education programs deliverable to industrial partners interacting with governments to assure the sustainable availability of medicines [24-27].

CONCLUSION

Biopharmaceutical engineering has redefined the paradigm of drug development by combining advanced biotechnology, molecular biology, and process engineering to produce more targeted, effective, and personalized therapies. While traditional pharmaceuticals still play a crucial role, the rise of biologics, monoclonal antibodies, and nucleic acid-based therapies is shifting the industry focus toward biologically derived solutions. The complex nature of biopharmaceuticals requires sophisticated production, purification, and formulation strategies, with Quality by Design and sustainable practices now central to regulatory and commercial success. Despite challenges such as high development costs, complex manufacturing requirements, and stringent quality controls, the field continues to evolve rapidly, driven by innovations in screening technologies, delivery systems, and process modeling. Case studies such as the development of Rituxan underscore the transformative potential of biopharmaceuticals. Looking forward, a multidisciplinary, sustainability-focused approach is essential for advancing therapeutic innovation while ensuring global accessibility, affordability, and environmental responsibility in healthcare.

REFERENCES

1. Jozala AF, Geraldes DC, Tundisi LL, Feitosa VD, Breyer CA, Cardoso SL, Mazzola PG, Oliveira-Nascimento LD, Rangel-Yagui CD, Magalhães PD, Oliveira MA. Biopharmaceuticals from microorganisms: from production to purification. Brazilian journal of microbiology. 2016 Dec;47(Suppl. 1):51-63.
2. Lalor F, Fitzpatrick J, Sage C, Byrne E. Sustainability in the biopharmaceutical industry: Seeking a holistic perspective. Biotechnology advances. 2019 Sep 1;37(5):698-707.

3. Wang X, Zhang S, Liu Y, Du J, Huang H. How pharmaceutical innovation evolves: The path from science to technological development to marketable drugs. Technological Forecasting and Social Change. 2021 Jun 1;167:120698.
4. Gaudilliere JP. Pharmaceutical innovation and its crisis: drug markets, screening, and the dialectics of value. BioSocieties. 2021 Sep;16(3):411-32.
5. Liu C, Constantinides PP, Li Y. Research and development in drug innovation: reflections from the 2013 bioeconomy conference in China, lessons learned and future perspectives. Acta Pharmaceutica Sinica B. 2014 Apr 1;4(2):112-9.
6. Arencibia AD, Di Sansebastiano G, Kumar V. Biotechnology of plant secondary metabolites: Phytochemical biopharming as a sustainable contribution to a high-tech bioeconomy. South African Journal of Botany. 2022;149:754-7.
7. Ugwu OP, Alum EU, Ugwu JN, Eze VH, Ugwu CN, Ogenyi FC, Okon MB. Harnessing technology for infectious disease response in conflict zones: Challenges, innovations, and policy implications. Medicine. 2024 Jul 12;103(28):e38834.
8. Muttenthaler M, King GF, Adams DJ, Alewood PF. Trends in peptide drug discovery. Nature reviews Drug discovery. 2021 Apr;20(4):309-25. google.com
9. Colen L, Belderbos R, Kelchtermans S, Leten B. Many are called, few are chosen: the role of science in drug development decisions. The Journal of Technology Transfer. 2024 Apr;49(2):492-517. nih.gov
10. Cottier B, Rahman R, Fattorini L, Maslej N, Besiroglu T, Owen D. The rising costs of training frontier AI models. arXiv preprint arXiv:2405.21015. 2024 May 31.
11. Tingle BI, Tang KG, Castanon M, Gutierrez JJ, Khurelbaatar M, Dandarchuluun C, Moroz YS, Irwin JJ. ZINC-22— A free multi-billion-scale database of tangible compounds for ligand discovery. Journal of chemical information and modeling. 2023 Feb 15;63(4):1166-76. acs.org
12. Khetan R, Curtis R, Deane CM, Hadsund JT, Kar U, Krawczyk K, Kuroda D, Robinson SA, Sormanni P, Tsumoto K, Warwicker J. Current advances in biopharmaceutical informatics: guidelines, impact and challenges in the computational developability assessment of antibody therapeutics. InMAbs 2022 Dec 31 (Vol. 14, No. 1, p. 2020082). Taylor & Francis. tandfonline.com
13. Ugwu CN, Ugwu OP, Alum EU, Eze VH, Basajja M, Ugwu JN, Ogenyi FC, Ejemot-Nwadiaro RI, Okon MB, Egba SI, Uti DE. Medical preparedness for bioterrorism and chemical warfare: A public health integration review. Medicine. 2025 May 2;104(18):e42289.
14. Blanco-Gonzalez A, Cabezon A, Seco-Gonzalez A, Conde-Torres D, Antelo-Riveiro P, Pineiro A, Garcia-Fandino R. The role of AI in drug discovery: challenges, opportunities, and strategies. Pharmaceuticals. 2023 Jun 18;16(6):891. mdpi.com
15. Bonaccorso A, Russo G, Pappalardo F, Carbone C, Puglisi G, Pignatello R, Musumeci T. Quality by design tools reducing the gap from bench to bedside for nanomedicine. European Journal of Pharmaceutics and Biopharmaceutics. 2021 Dec 1;169:144-55. [HTML]
16. Schad M, Gautam S, Grein TA, Käß F. Process Analytical Technologies (PAT) and Quality by Design (QbD) for bioprocessing of virus-based therapeutics. InBioprocess and Analytics Development for Virus-based Advanced Therapeutics and Medicinal Products (ATMPs) 2023 Aug 11 (pp. 295-328). Cham: Springer International Publishing. [HTML]
17. Mu'azzam K, da Silva FV, Murtagh J, Gallagher MJ. A roadmap for model-based bioprocess development. Biotechnology Advances. 2024 Jul 1;73:108378.
18. Ugwu CN, Ugwu OP, Alum EU, Eze VH, Basajja M, Ugwu JN, Ogenyi FC, Ejemot-Nwadiaro RI, Okon MB, Egba SI, Uti DE. Sustainable development goals (SDGs) and resilient healthcare systems: Addressing medicine and public health challenges in conflict zones. Medicine. 2025 Feb 14;104(7):e41535.
19. Sarkis M, Bernardi A, Shah N, Papathanasiou MM. Emerging challenges and opportunities in pharmaceutical manufacturing and distribution. Processes. 2021 Mar 3;9(3):457.
20. Koel M. Developments in analytical chemistry initiated from green chemistry. Sustainable Chemistry for the Environment. 2024 Mar 1;5:100078.
21. Shepherd J, Leake M. Invention, Innovation, and Commercialisation in British Biophysics. arXiv preprint arXiv:2504.11276. 2025 Apr 15.
22. Erickson J, Baker J, Barrett S, Brady C, Brower M, Carbonell R, Charlebois T, Coffman J, Connell-Crowley L, Coolbaugh M, Fallon E. End-to-end collaboration to transform

biopharmaceutical development and manufacturing. Biotechnology and Bioengineering. 2021 Sep;118(9):3302-12. wiley.com
23. Edyedu I, Ugwu OP, Ugwu CN, Alum EU, Eze VH, Basajja M, Ugwu JN, Ogenyi FC, Ejemot-Nwadiaro RI, Okon MB, Egba SI. The role of pharmacological interventions in managing urological complications during pregnancy and childbirth: A review. Medicine. 2025 Feb 14;104(7):e41381.
24. Schuhmacher A, Gassmann O, Bieniok D, Hinder M, Hartl D. Open innovation: A paradigm shift in pharma R&D?. Drug Discovery Today. 2022 Sep 1;27(9):2395-405.
25. Husnain A, Rasool S, Saeed A, Hussain HK. Revolutionizing pharmaceutical research: Harnessing machine learning for a paradigm shift in drug discovery. International Journal of Multidisciplinary Sciences and Arts. 2023 Sep 27;2(4):149-57. [HTML]
26. Paul-Chima UO, Ugwu CN, Alum EU. Integrated approaches in nutraceutical delivery systems: optimizing ADME dynamics for enhanced therapeutic potency and clinical impact. RPS Pharmacy and Pharmacology Reports. 2024 Oct;3(4):rqae024.
27. Yadav S, Singh A, Singhal R, Yadav JP. Revolutionizing drug discovery: The impact of artificial intelligence on advancements in pharmacology and the pharmaceutical industry. Intelligent Pharmacy. 2024 Feb 24.

CITE AS: Awafung Emmanuel (2025). Biopharmaceutical Engineering: Innovations in Drug Development. NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES 6(3):14-20 https://doi.org/10.59298/NIJSES/2025/63.1420