Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 12s (2025)
https://www.jneonatalsurg.com

OPEN ACCESS

Study of an Advanced DDS for Improving Efficacy and Precision of Healthcare Innovation

Dr. M. Vamsikrishna[1], Dr.J. Seetha[2], M. Sakthivel[3], Dr. A Hanumat Prasad[4], Dr. Maithili K[5], Chunduri Lavanya[6]

[1]Professor & HoD, Department of Computer Applications,School of Engineering, Aditya University,Kakinada.

Email ID: vkmangalampalli@gmail.com

[2]Professor, Department of Computer Science and Business Systems, Panimalar Engineering College, Chennai,INDIA-600123

Email ID: seetha.csbs@panimalar.ac.in

[3]Assistant professor, Department of Computer Science and Engineering, Vel Tech High Tech Dr Rangarajan Dr Sakunthala Engineering College Chennai, Tamilnadu, INDIA

Email ID: vel.sakthi@gmail.com,

[4]Associate professor, Department of CSE-AI&ML, Kallam Haranadhareddy Institute of Technology, chowdavaram,Guntur, Andhra Pradesh, INDIA - 522019

ORCID ID: 0000-0003-1897-2847

Email ID: hanuma.alahari@gmail.com

[5]Associate Professor, Department of CSE – AIML, KG Reddy College of Engineering and Technology , Hyderabad, Telangana, INDIA-500086

Email ID: drmaithili@kgr.ac.in

[6]Department of Computer Science and Engineering, KL University,Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, India - 522502

Email ID: lavanyabbch@kluniversity.in

Cite this paper as: Dr. M. Vamsikrishna, Dr.J. Seetha, M. Sakthivel, Dr. A Hanumat Prasad, Dr. Maithili K, Chunduri Lavanya, (2025) Study of an Advanced DDS for Improving Efficacy and Precision of Healthcare Innovation. *Journal of Neonatal Surgery*, 14 (12s), 255-264.

ABSTRACT

Nowadays, a modern healthcare system has been enhanced by incorporating the DDS (DDS) which is one of the most significant therapeutic interventions. Moreover, DDS is the latest advanced technological to overcome the limitations of the existing drug administration's such as bioavailability, low solubility, abbreviated half-life, etc. Here, this study discusses the recent technologies which based on healthcare innovation related models are explored.

Keywords: *healthcare innovation, drug administration, bioavailability, low solubility*

1. INTRODUCTION

last few decades, the creation of novel DDSs as well as biodegradable based biocompatible materials has transformed in to the medicine [1]. Moreover, these developments are have promoted in multidisciplinary cooperation among the chemists, clinicians, and biologists, while having the considerable influence on the biomedical domains, like tissue engineering as well as biomaterials knowledge [2]. Also, to get beyond the disadvantages of outmoded drug administration, DDSs macro and micro nano-scale carriers that transport therapeutic chemicals into the body are important [3]. They provide more and more suitability, growth the patient agreement, recover the drug safety, etc. therefore, the suitable and use of DDSs are now more important while comparing knowledge of pharmacokinetics and biodistribution continues to development. Conseqiently, these systems are planned to manage the therapeutic substances at a regulated rate and shield them from deterioration [4]. By preserving the drug attentions within the beneficial space, early DDSs, like macroscopic drug depots, assisted in lowering systemic toxicity [5]. But, because they were dependent on outside variables like pH, temperature, and ionic strength and

could only release their contents over a brief period of time as one day, their effectiveness was limited [6-9]. Moreover, advanced DDSs that can deliver extremely reproducible, controlled, and continued drug release in both in environments such as vino and vitro. Moreover, these environments have been designed for systemic and local therapy in order to overcome these problems. Some of these have even progressive to clinical trials, but the today's field-controlled drug release is still developing and has important uses in many medical fields, such as myocardial therapy, diabetes, cancer handling, pain managing, and ischemia [10-15].

Nevertheless, the time consumption is one of the patient-specific requirements, which are affects the physiological changes, the majority of carriers still only offer monotonic release profiles, contempt of the current famous developments in DDS frameworks [16]. Furthermore, somewhat actively monitoring the announcement rate, the encapsulating matrix mostly slows the drug issue [17].

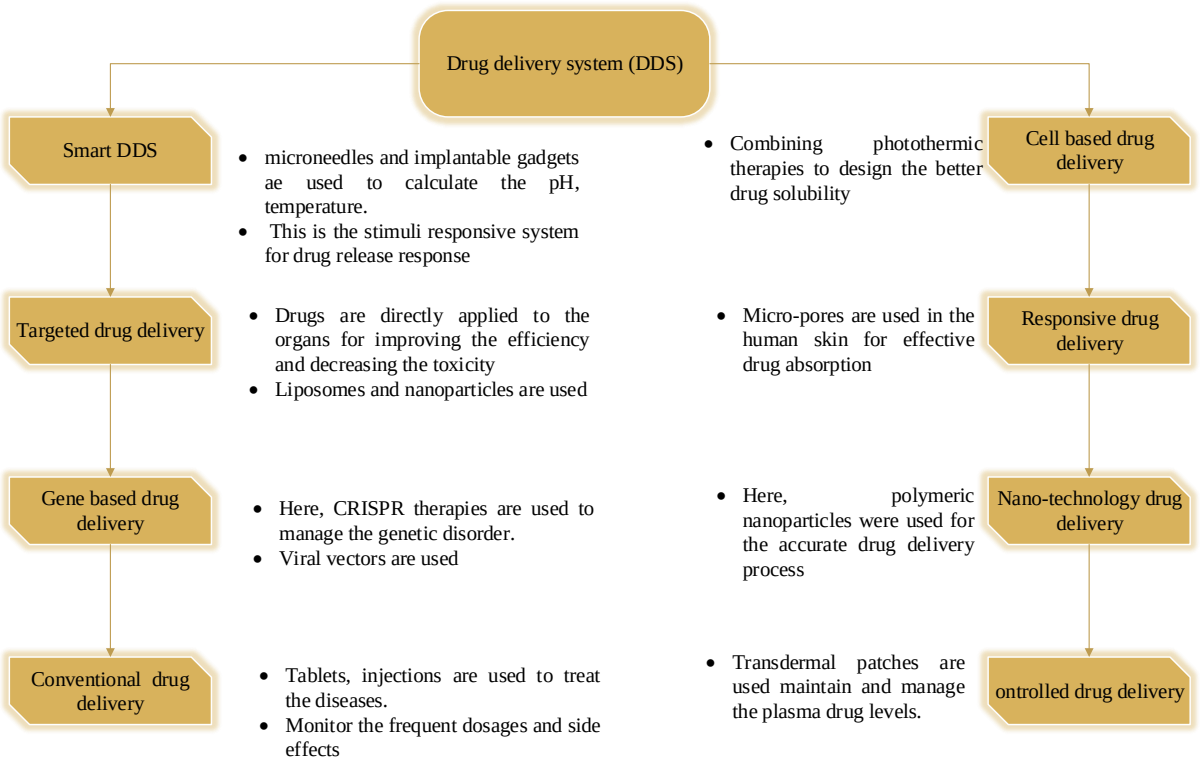

Fig. 1 Recent trends of DOS

Additionally, some therapeutic treatments like proteins and vaccines need to be directed exactly finished a prearranged interval, which has a big influence on their general effectiveness, constancy and bioavailability. Consequently, growing the treatment outcomes requires the long-term development of DDS with personalized plans and physicochemical features that are energetically adapts the statement outline in retort to altering states for all terms and services [18]. The majority of transporters still only hive a suggestion based on the patient-specific requirements, physiological changes, monotonic release profiles, irrespective of time, which are despite the recent distinguished advances in DDS. Stated differently, the encapsulating matrix does not actively control the release rate; rather, its primary job is to slow drug release [19-22]. Fast and better developments in manufacturing and materials science have made it possible to fabricate the complex DDSs with single release characteristics. theta are "Manageable" and "unmanageable" strategies are the two basic categories into which prevailing DDSs can be separated [23-25]. Also, drug release in controllable systems can be measured by superficially operating parameters which includes temperature, magnetic fields, light intensity, and ultrasonic frequency or magnitude, or by the interaction of smart materials with environmental stimuli [26].

2. BACKGROUND OF DDS

Drug delivery is a vital aspect of pharmaceutical science that focuses on designing and optimizing methods to administer therapeutic agents effectively while maximizing their benefits and minimizing adverse effects [27]. Traditional drug delivery approaches, such as oral ingestion, intravenous injections, and transdermal patches, often face challenges like poor solubility, low bioavailability, rapid metabolism, and systemic toxicity [28]. Advanced DDSs (DDS) have been developed to enhance

drug stability, improve controlled release, and enable targeted delivery to specific tissues or cells [29]. These systems include nanoparticles, liposomes, hydrogels, polymer-based carriers, and micro needles, which help improve therapeutic efficiency and reduce side effects [30]. Emerging technologies such as nanotechnology, gene therapy, and stimuli-responsive drug carriers have revolutionized drug delivery by enabling precise, localized treatment while minimizing systemic exposure [31]. Targeted drug delivery, particularly in cancer therapy, ensures that drugs reach diseased cells while sparing healthy tissues, thereby increasing treatment effectiveness and reducing toxicity [32].

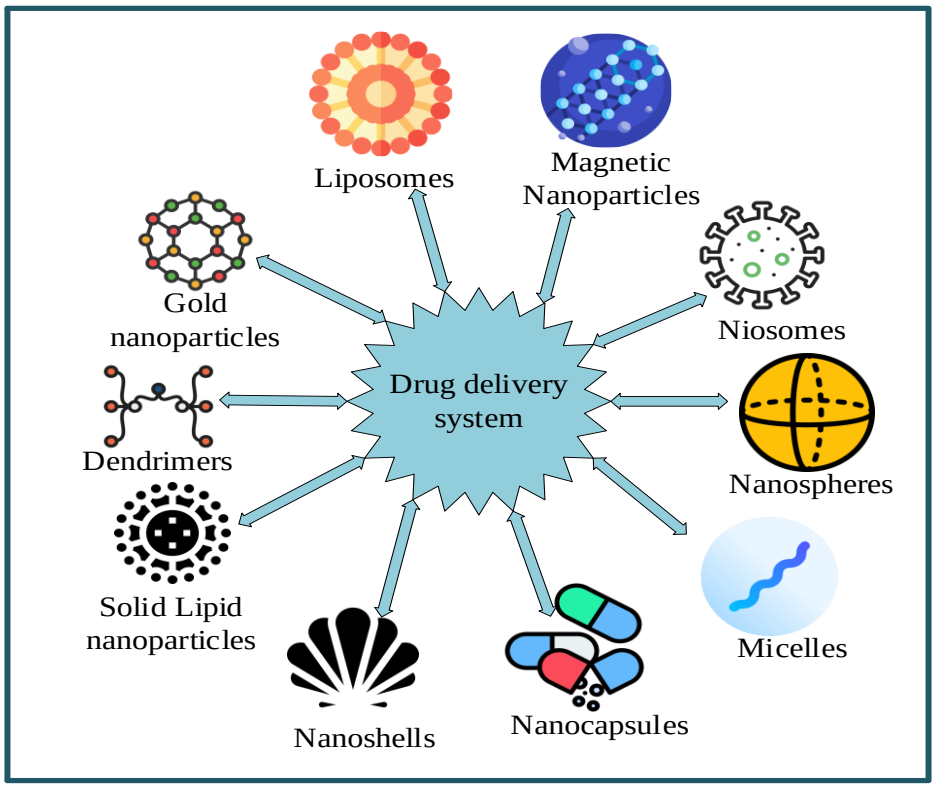

Figure 2 Elements of DDS

Figure 2 shows the elements of DDS, including liposomes, micelles, dendrimers, and nanoparticles [33]. These systems enhance drug stability, bioavailability, and targeted delivery, reducing side effects and improving treatment efficacy. Magnetic nanoparticles and gold nanoparticles offer controlled and site-specific drug release using external stimuli. Such advanced carriers revolutionize medicine by optimizing drug transport for cancer therapy, gene delivery, and other medical applications [34-37].

3. ADVANCED DOS INVENTION

DDSs control the release, absorption, and targeting of drugs to improve effectiveness and reduce side effects. They can regulate drug release over time, respond to biological triggers, or enhance precision through advanced biotechnologies. Modern approaches focus on improving patient compliance and treatment outcomes [38].

3.1 Transdermal DDSs

Transdermal DDSs (TDDS) deliver drugs through the skin into the bloodstream for systemic effects, offering a non-invasive alternative to oral and injectable routes [39]. These systems use patches, gels, or micro needles to enhance drug permeation through the skin barrier. TDDS provides controlled, sustained drug release, reducing dosing frequency and improving patient compliance. It bypasses first-pass metabolism, minimizing gastrointestinal side effects. Common applications include pain management, hormone therapy, and nicotine replacement. Advances in nanotechnology and bioengineered carriers are expanding TDDS for a wider range of drugs and personalized medicine [40].

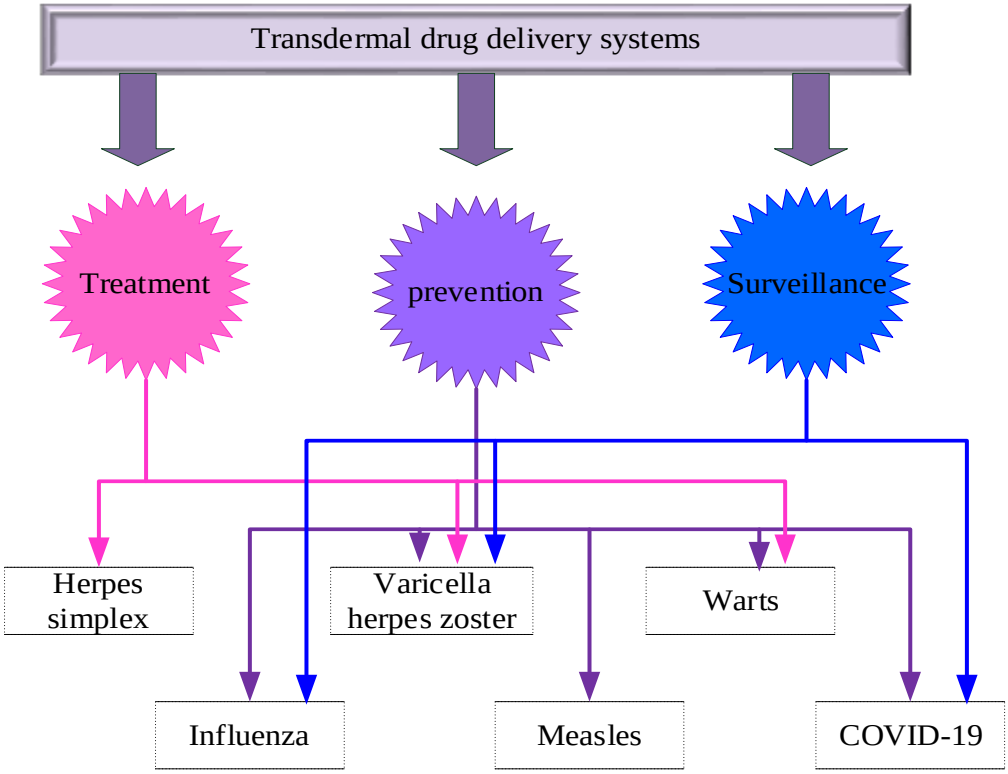

Figure 2 Transdermal DDSs

Figure 2 shows the transdermal DDSs categorized into treatment, prevention, and surveillance. These systems help manage diseases like herpes simplex, varicella, warts, influenza, measles, and COVID-19 through controlled drug release. This approach enhances drug absorption, reduces side effects, and improves patient compliance [41].

3.2 Oral DDSs

Oral DDSs (ODDS) are the most common and convenient method of drug administration, involving tablets, capsules, liquids, and suspensions. They offer ease of use, patient compliance, and cost-effectiveness but must overcome challenges like first-pass metabolism and variable absorption. ODDS can be designed for immediate, sustained, or controlled release to optimize therapeutic effects. Advanced formulations, such as nanoparticles and bio adhesive systems, enhance drug solubility and absorption. Continuous innovations in ODDS aim to improve bioavailability, target-specific delivery, and personalized medicine applications [42-45].

3.3 Nasal Drug Delivery

Nasal DDSs (NDDS) administer drugs through the nasal mucosa for local or systemic effects, offering a non-invasive and rapid-acting alternative to oral and injectable routes. They bypass first-pass metabolism, enhancing bioavailability and enabling direct drug transport to the brain via the olfactory pathway. NDDS includes sprays, drops, gels, and powders, commonly used for allergy treatments, pain relief, and vaccines. Challenges include mucociliary clearance and limited drug permeability, but advancements in nano carriers and bio adhesive formulations are improving drug retention and absorption [46-50].

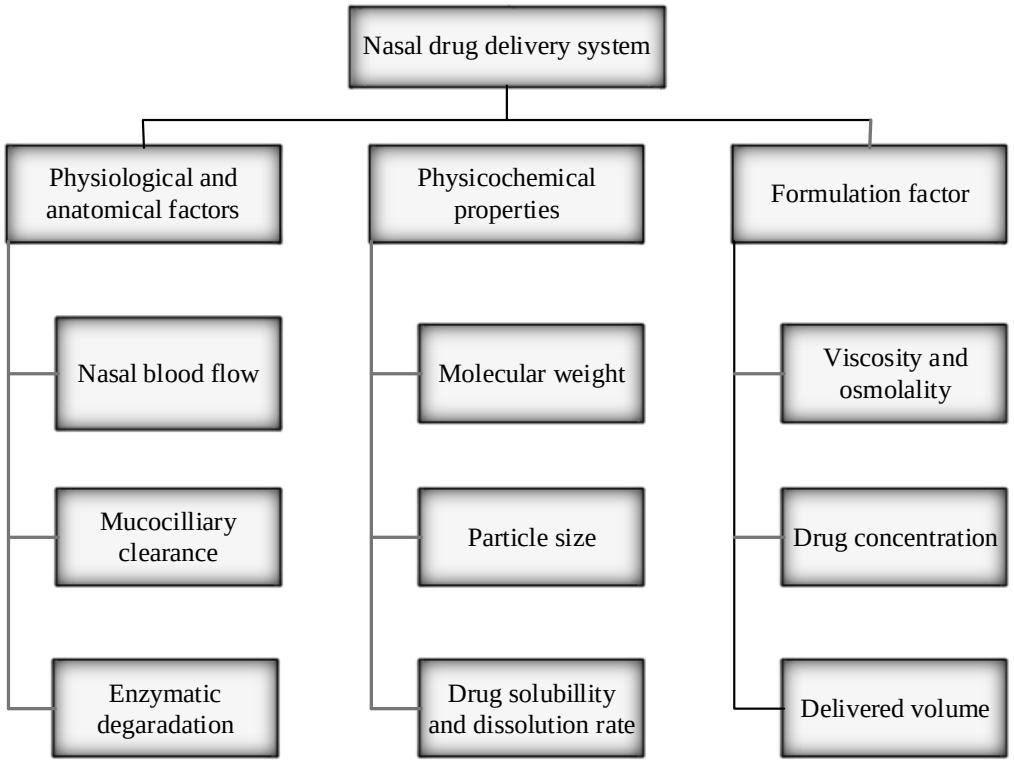

Figure 4 Nasal DDSs

Figure 4 shows the nasal DDS, categorized into physiological, physicochemical, and formulation aspects. Factors such as nasal blood flow, enzymatic degradation, molecular weight, viscosity, and drug solubility affect drug absorption and efficacy. Optimizing these parameters enhances nasal drug delivery for improved therapeutic outcomes [51].

4. DDS BASED HEALTHCARE INVENTION

DDS is defined as a formulation that authorizes the entry of the therapeutically active substance in the body and enhances its efficiency and safety by managing the time and the drugs place of release in the body. Figure 2 shows the DDS types [52].

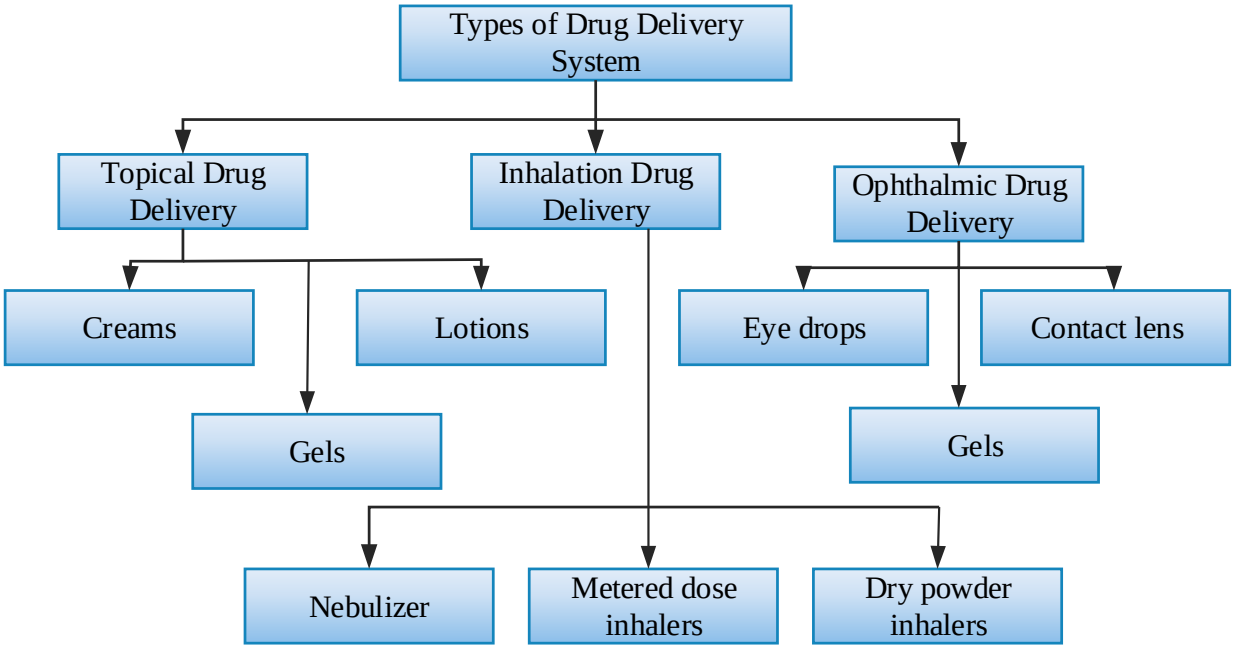

Figure 5. Types of DDS

Topical Drug Delivery:

The direct application of drugs onto the skin or mucosal surfaces for localized or systemic effects is the topical drug delivery. The formulations like creams, gels, ointments, lotions, and transdermal patches are included. These systems are broadly used for dermatological conditions, pain relief, and hormone therapy. Transdermal patches offer a controlled release of drugs into systemic circulation, bypassing first-pass metabolism. The drug penetration through the skin depends on factors like lipophilicity, skin permeability, and molecular size [53].

Inhalation Drug Delivery

Inhalation drug delivery controls the medications directly into the respiratory tract using devices like metered-dose inhalers (MDIs), dry powder inhalers (DPIs), and nebulizers. It is commonly used for respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD), and cystic fibrosis treatment. The significant advantage of inhalation therapy is its fast onset of action and localized effect with low systemic side effects. Particle size plays a important role, as drugs must be within the 1-5 µm range to reach the lungs deep alveolar regions effectively [54].

Ophthalmic Drug Delivery

Ophthalmic DDSs are designed to administer drugs to the eye for treating conditions like glaucoma, infections, and dry eye syndrome. Traditional formulations include eye drops, ointments, and gels, but newer systems like in situ gels, nanoparticles, and contact lens-based drug delivery are improving efficacy. The major challenges in ophthalmic drug delivery is rapid drug elimination due to blinking and tear drainage, necessitating frequent dosing or advanced sustained-release formulations for prolonged therapeutic effects [55].

Nanoparticle-based DDSs

Nanoparticle-based DDSs use nanoscale carriers to improve drug solubility, stability, and targeted delivery. These systems include liposomes, polymeric nanoparticles, dendrimers, micelles, and inorganic nanoparticles. They enhance bioavailability, protect drugs from degradation, and enable controlled or stimuli-responsive release.

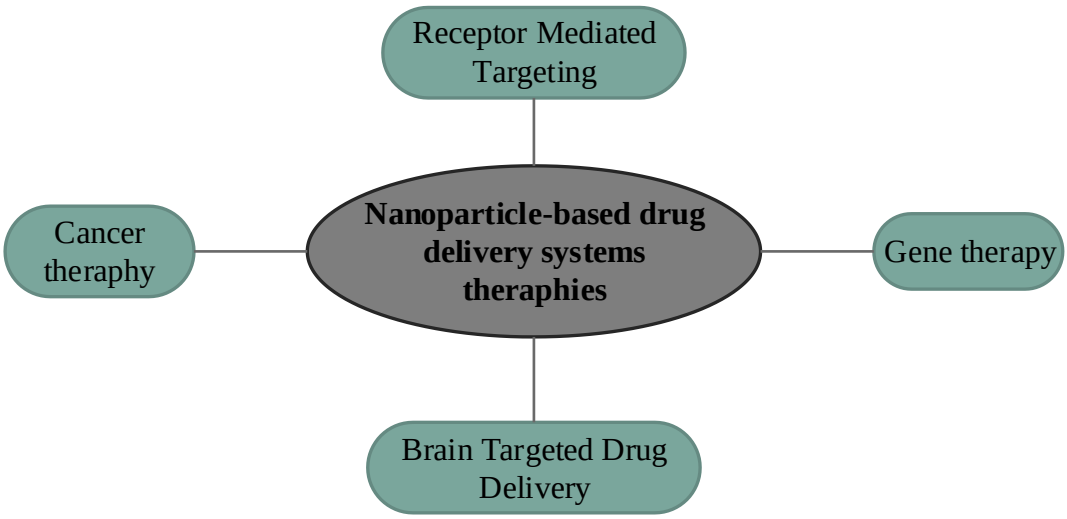

Figure 6. Nanoparticle-based DDSs

Figure 6 shows the DDS based on nanoparticles**.** A key advantage is their ability to deliver drugs precisely to diseased cells while minimizing systemic toxicity, making them highly effective in cancer therapy, gene therapy, and brain-targeted drug delivery. Functionalized nanoparticles can cross biological barriers, such as the blood-brain barrier, enabling treatment of neurodegenerative diseases. Additionally, surface modification with ligands enhances receptor-mediated targeting. Despite their potential, challenges like toxicity, large-scale production, and regulatory hurdles remain [56].

5. EVOLUTION OF DRUG DELIVERY:

The DDSs evolution has been a transformative journey, progressing from rudimentary methods of drug administration to sophisticated, controlled, and targeted systems. In olden days, medicines were derived from natural sources, such as herbs and plant extracts, and were administered using techniques like oral ingestion, topical application, or inhalation. With the advent of modern pharmaceuticals in the early 20th centuries, synthetic drugs like aspirin and penicillin emerged, along with innovations in tablets, capsules, and injectable formulations. These advancements permit for more precise dosing, improved stability, and enhanced therapeutic effects, setting the foundation for modern drug delivery. The late 20th century saw the introduction of controlled and sustained-release systems, such as transdermal patches, biodegradable microspheres, and

polymer-coated tablets, designed to enhance drug efficacy and patient compliance [57].

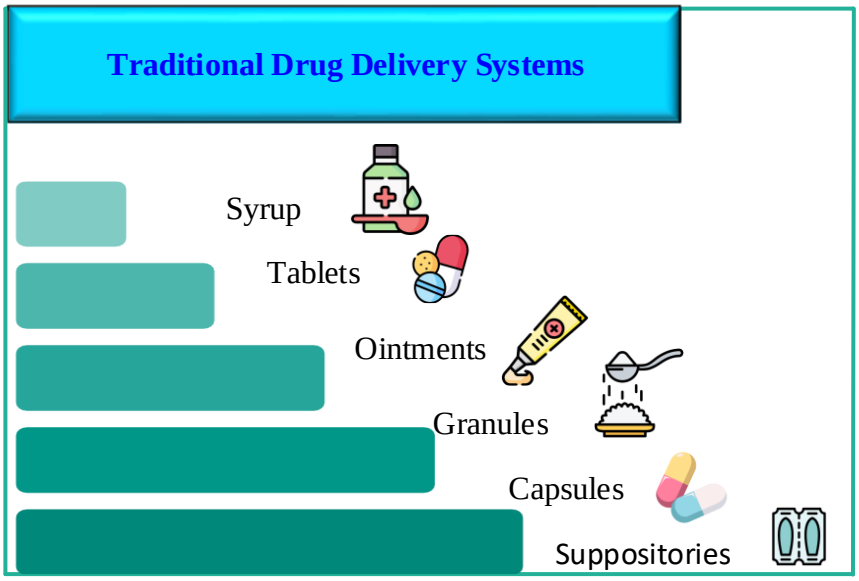

Figure 7. Healthcare based DDS

Figure 7 illustrates various traditional DDSs, including syrups, tablets, ointments, granules, capsules, and suppositories. In the 21st century, nanotechnology, gene therapy, and AI-driven drug delivery breakthrough have led to targeted treatments, particularly in cancer therapy, vaccine development, and personalized medicine [58].

6. RELATED STUDY AND CHALLENGES

DDS is turned as 3D printing devices to ensure the operations are properly assigned or not. here, 3D printing based Finite Element Analysis (FEA) was developed by Thomas profitiliotis et al, [59] to enhance the drug based healthcare industry. Moreover, data driven spot issues like down line and tweaks are optimized during the virtual laboratory. Consequently, treatment pals, therapy, feedback loops, embedded sensors are arranged according to the real time adaption system. therefore this 3-D printing DDS has most effective for this advanced filed.

integration of AI model with healthcare system is potential DDS to explores the privacy regulations and target identification through the model, which is developed by P.Arunachalam, R.Usharani, et al, [60]. this model has discuss about the drug efficacy and their safety measure during the usage of each drugs. then, ethical challenges related to the anonymization strategies which are highly impact by the cost and time of the drug discover system.

6.1 Challenges and limitations of DDS

The DDS plays a crucial role in ensuring that pharmaceutical compounds reach their intended targets in the body effectively and safely. However, several challenges exist in developing and optimizing these systems. Some key challenges include:

- Many drugs have low solubility and permeability, leading to poor absorption and reduced therapeutic effect. Drug modifications or advanced formulations are required to enhance bioavailability.
- Ensuring drugs reach specific tissues while minimizing side effects remains a major challenge. Targeted delivery methods, such as nanoparticles and liposomes, are being explored.
- Some drugs degrade due to pH changes, enzymatic activity, or environmental exposure. Stabilizing agents or encapsulation techniques help improve drug stability.
- Crossing the blood-brain barrier is difficult, limiting treatments for neurological diseases. Nano carriers and receptor-mediated transport are potential solutions.
- The body may recognize drug carriers as foreign, leading to immune rejection. Biocompatible materials and stealth coatings help evade immune detection.
- Diseases like cancer and bacterial infections develop resistance, reducing drug efficacy. Combination therapy and novel delivery mechanisms help overcome resistance.
- Frequent dosing or invasive delivery methods lower patient adherence. Controlled-release formulations and non-invasive routes improve compliance.

- Advanced DDS technologies require extensive research, making them expensive. Cost-effective production and scalability remain key challenges.
- Strict approval processes ensure safety but slow down the adoption of new DDSs. Extensive preclinical and clinical testing is needed for regulatory approval.
- Biodegradability and ethical concerns arise with novel drug carriers and formulations. Sustainable materials and ethical guidelines help address these issues.

7. CONCLUSION AND REGULATORY AND SAFETY CONSIDERATIONS OF DDS

Nanoparticles must be evaluated for cytotoxicity, immunogenicity, and long-term accumulation risks in tissues. Materials used should be non-toxic, biodegradable, and safe for human use. Pharmacokinetics and Bio distribution Studies are needed to understand nanoparticle absorption, metabolism, distribution, and excretion in the body. Stability and Shelf-Life must maintain in drug delivery for their structural integrity and therapeutic properties during storage and transportation. Manufacturing and Scalability of Regulatory bodies require consistency, reproducibility, and GMP compliance for large-scale production. Sterility and Contamination Control Nanoparticles must be free from microbial contamination and endotoxins to ensure patient safety. Clearance and Bioaccumulation must assess whether nanoparticles accumulate in organs, leading to potential toxicity. Transparent research and clinical testing are essential to address public concerns regarding nanoparticle safety. Post-Market Surveillance and Continuous monitoring for adverse effects, toxicity, or unexpected immune responses after commercialization.

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