MICROSPONGE DRUG DELIVERY SYSTEMS: A COMPREHENSIVE REVIEW ON DESIGN, DEVELOPMENT, AND THERAPEUTIC UTILITY

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ABSTRACT

Microsponge Drug Delivery Systems (MDDS) have emerged as a novel platform for achieving controlled, sustained, and targeted drug delivery. These porous, polymeric microspheres, typically ranging from 5 to 300 μm in diameter, exhibit a high surface area and internal porous structure, enabling effective encapsulation of both hydrophilic and lipophilic drugs. This comprehensive review elucidates the structure, composition, formulation techniques, characterization methods, and broad applications of MDDS in pharmaceutical and cosmetic domains. Preparation techniques such as quasi-emulsion solvent diffusion, suspension polymerization, and thermally induced phase separation are evaluated for their efficiency in achieving desired particle size, porosity, and entrapment efficiency. Key material choices—including ethyl cellulose, Eudragit RS100, and biodegradable polymers—are discussed in relation to their impact on drug release kinetics and matrix stability. Evaluation methodologies such as SEM, FTIR, BET analysis, and in vitro/in vivo release testing confirm the robust performance and versatility of these systems. Furthermore, recent innovations such as stimuli-

responsive and bioadhesive microsponges, nanosponges, and ligand-conjugated platforms demonstrate the expanding utility of MDDS in precision medicine, oncology, and vaccine delivery. Despite promising advances, challenges remain in scalability, regulatory approval, and long-term stability. Future directions highlight integration with nanotechnology, AI-driven personalization, and targeted delivery for chronic and systemic diseases. Overall, microsponges represent a transformative drug delivery strategy poised for next-generation therapeutics.

Keywords: Microsponge, Controlled release, Bioadhesive polymers, Stimuli-responsive systems, Oncology, Vaccine delivery.

1. INTRODUCTION

Drug delivery systems (DDS) have become an integral component of pharmaceutical science, significantly influencing the therapeutic efficacy, pharmacokinetics, and safety profile of drugs. Traditional dosage forms, such as tablets, capsules, and injections, often suffer from limitations including fluctuating plasma drug levels, poor patient compliance, and suboptimal targeting of the drug to the desired site of action. These limitations have fueled the development of advanced drug delivery systems that aim to optimize therapeutic outcomes by improving bioavailability, reducing dosing frequency, and minimizing adverse effects [1,2].Modern DDS can be classified into several categories, such as transdermal, oral, parenteral, ocular, and pulmonary delivery systems. Among these, controlled release systems are particularly notable for their capacity to maintain therapeutic drug concentrations over extended periods. These systems release the active pharmaceutical ingredient (API) in a predetermined, sustained, and predictable manner, resulting in enhanced patient compliance and reduced side effects [3].The necessity for controlled and site-specific drug delivery has grown in response to the challenges posed by conventional therapeutic regimens. For instance, systemic delivery often leads to off-target effects and toxicity, particularly in drugs with narrow therapeutic indices. Additionally, drugs with short biological half-lives require frequent dosing, which can cause patient inconvenience and reduce adherence [4].

Controlled drug delivery systems aim to overcome these challenges by precisely regulating the rate, time, and place of drug release. Targeted delivery systems, such as nanoparticles, liposomes, and microsponges, enhance drug accumulation at the disease site, thereby increasing the drug's efficacy while minimizing systemic exposure [5]. These systems are especially beneficial in the treatment of chronic diseases, cancer, and localized infections, where localized action and reduced systemic toxicity are crucial. Microsponge technology

represents an innovative class of polymer-based delivery systems designed to enhance the performance and safety of topically and orally administered drugs. Microsponges are porous, polymeric microspheres, typically ranging from 5–300 μm in diameter, capable of entrapping a wide range of active agents and releasing them in a controlled manner [6].

These microstructures are characterized by a high surface area, extensive porous architecture, and the ability to encapsulate both hydrophilic and lipophilic drugs. The porous nature allows microsponges to absorb skin secretions, thereby reducing greasiness and enhancing the drug's stability. Moreover, microsponges can modulate the release rate of drugs through diffusion and degradation-controlled mechanisms, which is essential for maintaining therapeutic levels over time [7].

Due to their flexibility in formulation and compatibility with various drug classes, microsponges have found extensive applications in dermatology (e.g., acne, hyperpigmentation), oncology, antifungal therapy, and cosmetic industries. They offer significant advantages such as improved drug stability, enhanced patient compliance, and minimal irritation at the site of application [8].Microsponge delivery technology was first developed in the early 1980s by Won, who patented the method for producing porous microspheres capable of entrapping active ingredients [9]. The technology was initially intended for topical applications, especially in cosmetics and dermatological formulations, owing to its oil-absorbing and sustained-release capabilities. Over the years, its utility expanded into pharmaceuticals due to its unique ability to offer time-controlled and environment-responsive drug release.The first commercial application of microsponge technology was seen in products such as Retin-A Micro® (tretinoin), where the system helped in minimizing the irritation typically associated with tretinoin while enhancing its efficacy. Since then, microsponge-based formulations have been developed for various drugs, including antifungals (e.g., ketoconazole), anti-inflammatory agents (e.g., diclofenac), and antibiotics (e.g., mupirocin), showing promising outcomes in both in vitro and in vivo studies [10,11].

Advances in polymer chemistry, microfabrication techniques, and pharmaceutical sciences have facilitated the design of tailored microsponge systems with specific release kinetics, environmental sensitivity (e.g., pH, temperature), and drug-loading capacity. Today, microsponge systems are considered a robust platform for targeted and controlled drug delivery, especially in topical, oral, and transdermal routes [12].

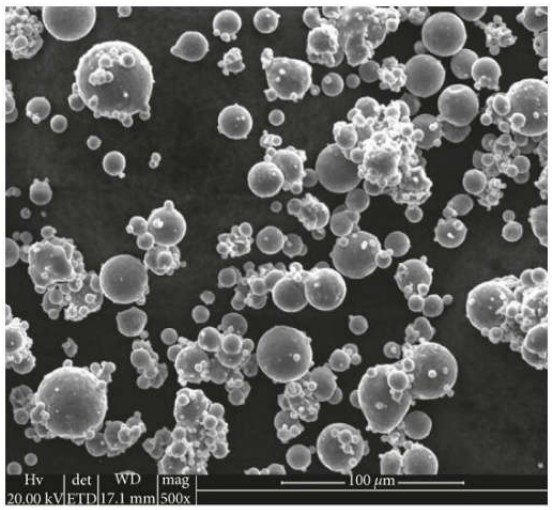

Figure 1: Scanning electron micrograph of the formed microsponges

2. STRUCTURE AND CHARACTERISTICS OF MICROSPONGES

2.1 Structural Composition

Microsponge drug delivery systems (MDS) are porous, polymer-based microcarriers typically ranging in size from 5–300 microns. These systems are mainly composed of cross-linked polymers such as ethyl cellulose, polystyrene, and Eudragit RS 100, which form a sponge-like matrix. This unique architecture is engineered using techniques like quasi-emulsion solvent diffusion and liquid–liquid suspension polymerization, enabling encapsulation of both hydrophilic and lipophilic drugs. The internal structure contains interconnecting voids and channels that provide high payload capacity and drug stability. Active pharmaceutical ingredients (APIs) are either dispersed within or adsorbed onto the porous scaffold. In recent developments, materials like polyvinyl alcohol (PVA) and carbopol have also been integrated for better biocompatibility and topical adhesion [13,14].

2.2 Porosity and Surface Area

Porosity and surface area are critical to the performance of microsponges. The highly porous structure, confirmed through techniques like mercury intrusion porosimetry and scanning electron microscopy (SEM), allows for large surface area-to-volume ratios. This enhances not only drug loading capacity but also the control over drug diffusion kinetics. Reports suggest that a typical microsponge can have porosity exceeding 60%, allowing for extensive surface interactions with solvents, enzymes, or targeted tissues [15].Moreover, BET (Brunauer–Emmett–Teller) analysis has been used to determine surface area profiles of microsponge

matrices, which can reach several hundred m^2/g, depending on the polymer used. This ensures uniform drug entrapment and gradual release [16].

2.3 Mechanism of Drug Entrapment and Release

The drug entrapment in microsponges occurs through physical entrapment within the polymeric matrix during the formation process. Depending on the drug and polymer characteristics, entrapment can be facilitated via solvent evaporation, diffusion, or adsorption. Controlled drug release is achieved through a diffusion-based mechanism, where the drug gradually escapes from the internal pores of the matrix into the external environment.This process is influenced by multiple factors such as polymer density, porosity, drug molecular weight, and the surrounding pH. MDS may exhibit zero-order, Higuchi, or Korsmeyer–Peppas kinetics, offering a sustained-release profile beneficial for chronic therapies [17].

Table 1: Advantages of Microsponge Drug Delivery Systems (MDS) [18]

Advantage	Description
Controlled and Sustained Release	Maintains steady drug levels for extended periods, reducing the need for frequent dosing.
Improved Drug Stability	Shields active pharmaceutical ingredients (APIs) from degradation due to environmental factors like light, heat, and oxidation.
Targeted Delivery	Facilitates localized drug action, especially in topical and transdermal applications, minimizing systemic exposure.

Advantage	Description
Enhanced Patient Compliance	Results in less irritation, better cosmetic feel, and convenient application—leading to improved adherence.
Reduced Side Effects	Gradual and controlled drug release prevents plasma concentration spikes, reducing the risk of toxicity.

3. MATERIALS USED IN MICROSPONGE FORMULATION

Microsponge Drug Delivery Systems (MDS) are porous microspheres widely explored for their controlled release capabilities, especially in topical and transdermal applications. The efficiency of these systems significantly depends on the choice of formulation materials. These include polymers, solvents, plasticizers, surfactants, and carefully selected excipients based on physicochemical compatibility and performance goals.

3.1 Polymers

Polymers form the backbone of the microsponge structure, playing a crucial role in encapsulation, release kinetics, mechanical strength, and biocompatibility. Three main types of polymers are frequently used in microsponge formulations:

Ethyl Cellulose

Ethyl cellulose is a hydrophobic polymer that offers sustained drug release and enhances the mechanical strength of microsponges. It is often used in quasi-emulsion techniques to form porous networks that are stable and inert. Its non-toxic and biocompatible nature makes it an ideal candidate for both topical and oral formulations [19].

Eudragit RS 100

This polymethacrylate polymer is known for its pH-independent release profile and high permeability. It imparts flexibility and toughness to the microsponge matrix and is especially useful in drug delivery systems that require extended drug release without degradation in acidic or basic environments [20].

Polylactic Acid (PLA)

A biodegradable and biocompatible polymer, PLA is commonly employed for controlled release in systemic applications. It offers a slow degradation profile, making it suitable for long-acting depot formulations. PLA-based microsponges are often used in anti-inflammatory and anticancer therapies [21].

3.2 Solvents

Solvents play a critical role in solubilizing the drug and polymer during microsponge formation. Their volatility and miscibility affect porosity, particle size, and drug loading efficiency.

Dichloromethane (DCM)

DCM is a volatile, water-immiscible organic solvent used extensively in the emulsion solvent diffusion method. It allows for the rapid precipitation of the polymer, leading to the formation of highly porous and spherical microsponges. However, concerns regarding residual solvent toxicity necessitate thorough drying [22].

Ethanol

Ethanol, a less toxic alternative, is used as a co-solvent to improve polymer solubility and facilitate emulsification. It helps in forming a stable quasi-emulsion and is often preferred when the drug is sensitive to harsher organic solvents [23].

3.3 Plasticizers and Surfactants

Plasticizers

Plasticizers like dibutyl phthalate or triethyl citrate are added to improve the flexibility and mechanical integrity of the polymer matrix. They reduce the glass transition temperature (Tg), facilitating better polymer film formation during microsponge synthesis [24].

Surfactants

Surfactants such as Tween 80, Span 60, or polyvinyl alcohol (PVA) stabilize the emulsion and reduce interfacial tension between the polymer-solvent phase and aqueous phase. Their concentration directly influences particle size and entrapment efficiency [25].

Table 2. Selection Criteria for Excipients in Microsponge Drug Delivery Systems

Criterion	Description	Evaluation Methods
Drug–Polymer Compatibility	Ensures no physical or chemical interaction between the drug and polymer that could affect efficacy.	DSC, FTIR Spectroscopy
Stability Enhancement	Enhances product shelf-life and prevents degradation, crystallization, or precipitation.	Stability testing (accelerated and real-time)
Functional Performance	Enables controlled drug release—immediate, sustained, or delayed—based on therapeutic requirements.	In vitro dissolution studies, release kinetics modeling
Toxicological Safety	Excipients must be non-toxic, inert, and pharmaceutically acceptable.	Reference to ICH guidelines, toxicology data, pharmacopeial reviews

4.METHODS OF PREPARATION OF MICROSPONGE DRUG DELIVERY SYSTEMS

Microsponge drug delivery systems (MDDS) are advanced, porous microspheres primarily developed for sustained and targeted drug release. The design and fabrication of these systems are significantly influenced by the method of preparation, each of which affects the physicochemical properties such as porosity, particle size, drug entrapment efficiency, and release kinetics. Below is a detailed overview of the primary methods used for preparing microsponges.

4.1 Quasi-emulsion Solvent Diffusion Method

The quasi-emulsion solvent diffusion method is one of the most widely employed techniques for microsponge synthesis due to its simplicity and efficiency. This method involves preparing an internal organic phase containing the polymer (commonly ethyl cellulose or polymethyl methacrylate) and the drug in a volatile solvent like dichloromethane or ethanol. This internal phase is then emulsified into an aqueous external phase containing a surfactant such as polyvinyl alcohol (PVA), leading to the formation of quasi-emulsion droplets.As the solvent diffuses from the internal phase into the aqueous phase, it leads to polymer precipitation, resulting in microsponge formation. Key parameters influencing the outcome include stirring speed, polymer-to-drug ratio, solvent evaporation rate, and surfactant concentration, which control microsponge size and entrapment efficiency [26].

4.2 Liquid–Liquid Suspension Polymerization

This method is particularly suitable when the monomer undergoes polymerization in the presence of a porogen. The process involves the dispersion of monomers (such as methyl methacrylate) and the drug in a continuous phase (commonly water), along with a cross-linking agent and initiator. Polymerization occurs upon heating or exposure to a catalyst, producing porous microsponge structures.Liquid–liquid suspension polymerization is advantageous for preparing microsponges with high thermal and mechanical stability. However, it often requires stringent control over reaction parameters, including temperature, pH, and monomer ratios, to achieve reproducible microsponge characteristics [27].

4.3 Diffusion-Controlled Methods

In these methods, the solvent containing both the drug and polymer diffuses into a non-solvent (often water), triggering polymer precipitation and the formation of a porous matrix. Unlike quasi-emulsion methods that rely on emulsification, diffusion-controlled techniques involve the controlled migration of solvents and non-solvents across phases.

These methods allow fine control over the microsponge’s pore size and drug loading efficiency. Parameters such as solvent type, miscibility, and rate of diffusion significantly impact the final microsponge architecture [28].

4.4 Thermally Induced Phase Separation

Thermally induced phase separation (TIPS) utilizes the principle of lowering the polymer solution's temperature to induce demixing of the solvent and polymer. This leads to the creation of a solid porous structure upon removal of the solvent.TIPS is useful when thermolabile drugs are not involved, as the method may include exposure to sub-ambient temperatures or heating. The pore structure and morphology of the resulting microsponges are highly tunable based on polymer concentration and cooling rate [29].

Table 3: Key Factors Influencing the Preparation of Microsponge Drug Delivery Systems [30]

Factor	Description
Polymer type and concentration	Determines the mechanical strength and porosity of the microsponges.
Solvent volatility	Affects the rate of polymer precipitation and the resultant particle size.
Stirring speed	Influences particle size distribution and uniformity of the formed microsponges.
Surfactant type and concentration	Impacts emulsion stability and affects the morphology of microsponge particles.
Temperature and pH of medium	Critical for polymerization and precipitation processes; affects reaction kinetics and stability.
Drug-to-polymer ratio	Determines drug entrapment efficiency and modulates release kinetics.

5. DRUG LOADING AND RELEASE MECHANISMS

5.1. Drug Entrapment Efficiency

Entrapment efficiency (EE) is a critical parameter in MDDS design, representing the percentage of drug successfully incorporated into the microsponges. High EE indicates optimal

formulation, reduces drug wastage, and improves therapeutic outcomes. Multiple studies report EE values ranging from 50–95%, depending on factors such as drug solubility, polymer type (e.g., ethyl cellulose, Eudragit RS100), cross-linking density, and emulsification method used during preparation [31,32]. For instance, Alburyhi et al. [33] evaluated lornoxicam-loaded microsponges and reported EE above 80% using quasi-emulsion solvent diffusion. Similarly, Deshmukh and Yadav optimized EE via in silico modeling for colorectal drug delivery, achieving high drug loading through factorial design approaches [34].

5.2. Release Kinetics

Release kinetics determines how the drug diffuses from the microsponge matrix into the surrounding medium. MDDS typically provide controlled or sustained drug release, making them highly suitable for chronic therapies. Drug release is governed by both diffusion-controlled and erosion-controlled mechanisms, often displaying biphasic release—an initial burst followed by a sustained phase [35,36]. For example, Mahmoud et al. [37] formulated a gastroretentive microsponge for mitiglinide calcium showing prolonged release over 24 hours. Studies consistently use in vitro release studies to characterize kinetics, often comparing profiles against pure drug release, confirming enhanced control due to porous matrix entrapment [38].

Table 4: Factors Influencing Release Behavior

Factor	Effect on Drug Release	Citation
Polymer concentration	Higher polymer content increases matrix density, leading to slower drug diffusion and extended release	[39]
Pore structure & cross-linking	Smaller, denser pores restrict drug diffusion, while looser matrices enhance release	[40]
Drug–polymer affinity	Stronger hydrophobic interactions (e.g., with curcumin, celecoxib) retard drug diffusion	[41]

Factor	Effect on Drug Release	Citation
Environmental pH	pH-sensitive polymers modulate drug release in targeted regions like colon or stomach	[42]
Stirring rate & temperature (preparation)	Affects microsponge morphology and size, which influence surface area and release rate	[43]

5.3. Mathematical Models Used for Release Profile Prediction

Table 6: summary of the Mathematical Models Used for Release Profile Prediction in Microsponge Drug Delivery Systems (MDDS).

Model Name	Release Mechanism	Suitability	Application in MDDS	Citation
Zero-order kinetics	Constant drug release over time	Ideal for systems requiring steady drug levels; rarely achieved in practice	Rarely observed in MDDS; only in highly optimized formulations with perfect matrix design	[44]
First-order kinetics	Release rate proportional to drug concentration remaining	Suitable for water-soluble drugs; concentration-dependent release	Describes common MDDS profiles, especially when drug is loosely bound to the matrix	[45]
Higuchi model	Diffusion-controlled release	Best fit for porous matrix systems like microsponges	Frequently observed in MDDS due to their porous polymeric structure enabling Fickian diffusion	[46]

Model Name	Release Mechanism	Suitability	Application in MDDS	Citation
Korsmeyer–Peppas model	Empirical; identifies Fickian vs non-Fickian transport	Versatile model, especially when mechanism is not clearly defined	Used to differentiate anomalous (non-Fickian) release in complex microsponge matrices	[47]

6. EVALUATION AND CHARACTERIZATION

6.1. Particle Size and Morphology (SEM, TEM)

The particle size and morphology of microsponges are pivotal in determining drug release kinetics, penetration behavior, and loading capacity. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are widely used tools for this purpose. SEM typically reveals spherical and porous microsponge structures with rough surfaces, indicating their drug-loading capability [48]. TEM, though less commonly used, provides ultrastructural details, especially useful in visualizing nanostructures or nanosized pores within the sponge matrix. Particle size typically ranges between 5–300 μm. A narrow size distribution often correlates with more uniform drug release [49].

6.2. Surface Area and Porosity (BET Analysis)

BET (Brunauer-Emmett-Teller) analysis is used to determine the surface area and porosity, both essential for evaluating the adsorption capacity and drug entrapment potential. Microsponges with higher surface areas and controlled porosity enhance the drug release rate due to increased contact with the dissolution medium. Studies on lornoxicam and benzoyl peroxide microsponges revealed that BET surface area ranged between 60–120 m^2/g with pore diameters around 0.1–0.3 μm, affirming suitability for sustained delivery [50].

6.3. Compatibility Studies (FTIR, DSC)

Drug-polymer compatibility is a critical evaluation step, ensuring stability and performance of microsponges. Fourier Transform Infrared Spectroscopy (FTIR) helps detect any interaction through shifts or disappearance of characteristic peaks. Differential Scanning Calorimetry (DSC) assesses thermal behavior and confirms physical state transitions. Studies indicate that

no significant chemical interaction occurs when using polymers like Eudragit RS100 or ethyl cellulose with various drugs such as curcumin, meloxicam, or sertaconazole, suggesting stable formulations [51].

6.4. Drug Content and Encapsulation Efficiency

Drug content represents the actual quantity of drug loaded, whereas encapsulation efficiency indicates the percentage of drug successfully entrapped in the sponge matrix relative to the theoretical amount. These parameters are typically analyzed via UV-Visible spectrophotometry or HPLC. Microsponges show a wide encapsulation range, usually between 60–85%, which is influenced by factors like polymer-drug ratio, stirring speed, and solvent evaporation method [52].

6.5. In Vitro and In Vivo Drug Release Studies

In vitro drug release studies are conducted in simulated biological environments using dialysis membranes, Franz diffusion cells, or USP apparatuses. These tests help simulate the controlled release properties of the microsponges. Formulations like voriconazole and sertaconazole microsponges exhibited sustained drug release over 12–24 hours in vitro [53]. In vivo studies, although less common, have demonstrated prolonged drug plasma levels and better therapeutic efficacy with reduced dosing frequency, such as with meloxicam and curcumin-based microsponges in animal models [54].

7.APPLICATIONS OF MICROSPONGE SYSTEMS

Microsponge Drug Delivery Systems (MDS) represent a unique and versatile platform known for their porous, polymeric architecture, which allows for controlled and targeted release of active ingredients. Their high loading capacity, reduced side effects, and controlled release mechanisms have led to a diverse range of therapeutic applications. Below, we examine their applications across various pharmaceutical and personal care sectors:

7.1. Topical Drug Delivery

Microsponge systems have been predominantly applied in topical formulations for treating dermatological conditions such as acne, fungal infections, and hyperpigmentation. Due to their capacity for controlled release and non-greasy texture, they improve patient compliance and minimize irritation. One of the earliest successful commercial applications includes Retin-A

microsponges for acne management, which reduce erythema and improve penetration without over-dosing the skin.

Antifungal agents like ketoconazole and clotrimazole have been effectively incorporated into microsponge formulations to provide sustained antifungal action over extended periods, improving patient outcomes in fungal dermatitis [55,56].

7.2. Oral Drug Delivery

Microsponge formulations have proven beneficial in oral delivery, especially for non-steroidal anti-inflammatory drugs (NSAIDs) like lornoxicam, diclofenac, and indomethacin, which often cause gastric irritation when administered in conventional form. Microsponge carriers allow for slow release in the intestinal tract, improving therapeutic efficacy while minimizing side effects such as peptic ulcers and gastric bleeding.

Moreover, anti-ulcer agents like omeprazole and ranitidine have been integrated into microsponges to prevent degradation in the stomach and enable site-specific release in the duodenum [57].

7.3. Ophthalmic and Pulmonary Applications

While still under intensive research, the use of microsponge systems in ocular and pulmonary drug delivery shows immense promise. For ophthalmic uses, microsponges can offer prolonged retention time in the ocular cavity without triggering immune response or irritation. They enhance bioavailability of poorly water-soluble drugs and reduce the frequency of administration in chronic eye conditions such as glaucoma or conjunctivitis.In pulmonary delivery, microsponges are being investigated for aerosol-based administration, where they offer advantages such as enhanced dispersion, mucosal adhesion, and reduced systemic side effects. These systems may be ideal for drugs used in asthma and chronic obstructive pulmonary disease (COPD) [58].

7.4. Cosmetic and Personal Care Products

Microsponge systems have gained widespread use in the cosmetic industry for delivering skin-lightening agents, anti-aging compounds, sunscreens, and fragrance retention. Active ingredients like kojic acid, vitamin E, and niacinamide are stabilized and released gradually,

improving skin compatibility and product performance.Furthermore, microsponges prevent greasiness, reduce volatility, and improve sensory feel, making them ideal for night creams, lotions, and deodorants. The sustained release profile also extends the product's effectiveness over time [59].

7.5. Targeted Drug Delivery Systems

Microsponge carriers can be designed to target specific tissues or organs, increasing therapeutic precision while minimizing off-target toxicity. Researchers are exploring ligand-conjugated microsponges and pH-sensitive polymers that release drugs only in specific microenvironments, such as the acidic tumor microenvironment in cancer therapy or the colon for inflammatory bowel disease.This targeting potential opens doors for chemotherapeutic, immunotherapeutic, and gene delivery applications, though more translational research is required before widespread clinical adoption [60,61].

8. RECENT ADVANCES AND PATENTS IN MICROSPONGE DRUG DELIVERY SYSTEMS

Microsponge Drug Delivery Systems (MDDS) have evolved significantly beyond conventional topical applications. The recent progress in this field involves sophisticated polymer chemistries, the development of intelligent or stimuli-responsive carriers, nanosponge transformations, and growing intellectual property through robust patent portfolios. The innovations aim to improve drug encapsulation, site-specific delivery, and release kinetics, with enhanced patient compliance and commercial viability.

8.1. Novel Polymers and Techniques

Recent trends in MDDS highlight the integration of novel polymers that enhance mechanical stability, drug retention, and release control. The evolution of biodegradable and bioresponsive polymers such as *ethyl cellulose*, *polyhydroxybutyrate-co-hydroxyvalerate (PHBV)*, and *β-cyclodextrin* has enabled the encapsulation of both hydrophobic and hydrophilic drugs in microsponge matrices [62]. Innovative fabrication methods like *quasi-emulsion solvent diffusion*, *nano-spray drying*, and *3D-printed microstructuring* have enhanced precision in particle morphology and drug loading efficiencies.

Researchers like Kumari et al. have demonstrated smart polymer blends that enhance drug entrapment and facilitate sustained release profiles in a more controlled environment [63].

Furthermore, Osmani et al. discussed the importance of amphiphilic block copolymers, which are tailored to improve the encapsulation of poorly water-soluble compounds [64].

8.2. Smart Microsponges (Stimuli-Responsive Systems)

Smart microsponges represent the next-generation carriers that respond to environmental stimuli like pH, temperature, or redox conditions to trigger drug release. These systems are especially useful in cancer therapy, where tumor-specific stimuli can activate targeted drug delivery. Recent studies include pH-sensitive microsponges for colon-specific release and thermosensitive sponges for inflammatory skin conditions [65].

Nandi et al. developed enzyme-responsive microsponge systems for bio-targeted anticancer applications, while Srivastava emphasized glucose-responsive microsponge systems suitable for diabetic wound healing applications [66,67]. These smart systems demonstrate higher precision in pharmacokinetics and pharmacodynamics, reducing side effects and enhancing therapeutic indices.

8.3. Nanosponges and Their Advantages

Nanosponges are nanometric counterparts of microsponges offering enhanced surface area, penetration, and drug loading capacity. Cyclodextrin-based nanosponges have emerged as a dominant class due to their inclusion complexation ability, allowing efficient encapsulation of volatile and poorly soluble drugs [68]. Unlike traditional microsponges, nanosponges exhibit better cellular uptake and are suitable for both topical and systemic routes.

Kandekar et al. outlined their benefits in transdermal systems for antifungal and antihistaminic drugs, while Mullick et al. detailed their use in skin targeting with reduced systemic exposure [69]. Nanosponges are also compatible with injectable formulations, making them versatile carriers for parenteral applications [70].

8.4. Key Patents Filed and Commercial Formulations

The intellectual property landscape for MDDS has expanded dramatically. One of the earliest and most influential patents was awarded to *Advanced Polymer Systems* (US Patent No.

4,690,825) for a novel microsponge system [71]. Since then, a series of patents have been filed covering materials, synthesis methods, and drug release mechanisms.

Recent patents include those for:

- pH-responsive microsponge gels for colon cancer (WO2023189474A1)
- Injectable nanosponge platforms for antineoplastic drugs (US20230329276A1)
- Cyclodextrin nanosponges for antiviral delivery (EP3819923A1)

Commercially, **Retin-A Micro®** (Johnson & Johnson) is a prominent topical formulation using microsponge technology for acne. Other examples include **Carac® cream** and **Flurandrenolide sponge-based tapes** used for corticosteroid delivery [72].

9. CHALLENGES AND LIMITATIONS IN MICROSPONGE DRUG DELIVERY SYSTEMS (MDS)

Microsponge Drug Delivery Systems (MDS) have emerged as promising carriers for controlled and targeted drug delivery, especially in dermatological and transdermal applications. Despite their numerous advantages, including high loading capacity, enhanced stability of active compounds, and controlled release behavior, their practical and commercial application faces several critical challenges. These limitations span across manufacturing scalability, regulatory frameworks, and reproducibility issues, which must be addressed for their mainstream clinical adoption.

9.1 Scale-up and Manufacturing Difficulties

The translation of microsponge systems from laboratory research to industrial-scale production remains a formidable challenge. Techniques such as quasi-emulsion solvent diffusion, liquid-liquid suspension polymerization, and emulsion polymerization—though effective in the lab—do not always yield consistent particle morphology, drug entrapment efficiency, or polymer integrity during scale-up.

During scale-up, factors such as mixing speed, temperature control, solvent evaporation rates, and polymer-drug interactions require meticulous optimization. Even minor deviations in formulation conditions may lead to significant batch-to-batch variability. Moreover, maintaining the spherical morphology and porous architecture at scale becomes difficult due to equipment limitations and inconsistencies in emulsification [73].

For instance, Halder et al. (2024) noted that optimization of stirring speeds and the use of scale-up compatible solvents were crucial but not sufficient in maintaining desired microsponge characteristics. Similarly, Junqueira and Bruschi (2018) pointed out that the in-process control strategies for pore size uniformity and drug dispersion are limited and need advanced inline analytical technologies [74].

9.2 Regulatory Aspects

One of the most pressing challenges in microsponge technology is the absence of clear regulatory guidelines specifically tailored to this class of drug delivery systems. MDS often falls between conventional topical formulations and nanocarriers, making classification difficult for approval purposes. Regulatory bodies like the FDA and EMA currently assess MDS under broader categories such as "modified-release" or "topical semisolid formulations," which may not adequately address the unique pharmacokinetic behavior and release dynamics of microsponge systems. The lack of compendial standards further complicates dossier preparation for new drug applications.

Padhi and Ahmed (2024) emphasize that despite promising preclinical outcomes, several microsponge-based formulations remain shelved due to uncertainty in regulatory pathways. The authors recommend the need for dedicated guidance documents to streamline formulation development and approval processes [75].

9.3 Reproducibility and Stability Concerns

Reproducibility is a cornerstone of pharmaceutical quality assurance, and microsponge systems often face significant variability in particle size, drug loading, and release kinetics across batches. Environmental conditions such as humidity, storage temperature, and pH can alter the porosity and swelling behavior of microsponges, thereby affecting drug release profiles.

Stability testing of MDS under ICH guidelines has also revealed issues with polymer degradation, drug-polymer incompatibility, and loss of drug from the sponge matrix over time. Rathi et al. (2024) highlight that microsponges loaded with volatile or photosensitive compounds undergo accelerated degradation unless protected by sophisticated secondary packaging [76].Moreover, Ravi et al. (2019) noted that long-term physical stability, especially in formulations containing hydrophobic drugs, remains an issue, often leading to sedimentation and loss of homogeneity in semisolid dosage forms [77].

10. FUTURE PERSPECTIVES OF MICROSPONGE DRUG DELIVERY SYSTEMS

10.1. Integration with Nanotechnology

The integration of microsponge systems with nanotechnology is a promising frontier. Microsponges, traditionally microporous spheres with sizes ranging from 5 to 300 μm, are now being miniaturized using nano-engineered polymers to combine the benefits of nano-carriers and micro-architectures. This hybrid design enhances drug entrapment efficiency, surface-to-volume ratio, and cellular uptake, thereby opening avenues for targeted intracellular drug delivery. Nano-enabled microsponges, when combined with surface modifications like PEGylation or ligand conjugation, may bypass biological barriers like the blood-brain barrier (BBB), allowing for site-specific delivery in neurological disorders. For example, studies have shown improved delivery of anticancer agents using nanoscale microsponges embedded with magnetic nanoparticles for magnetically guided release systems [78].

10.2. Personalized and Precision Medicine

The adaptability of microsponges in loading a wide variety of therapeutic agents (hydrophilic and lipophilic) and customizing release kinetics makes them highly suitable for precision medicine. Using patient-specific formulations—potentially supported by 3D-printing technologies and AI-driven drug profiling—microsponges could be tailored to individual pharmacogenomic profiles. This would ensure optimized therapeutic windows and minimized side effects.With the rise of pharmacogenetics, microsponges could serve as programmable devices for time-based and need-specific drug administration in diseases like diabetes, hypertension, and autoimmune disorders [79].

10.3. Bioadhesive and Stimuli-Responsive Microsponges

Emerging research is focused on developing bioadhesive microsponges that can attach to mucosal linings (e.g., gastrointestinal, buccal, vaginal, or ocular), increasing retention time and improving drug absorption. These microsponges are often fabricated with mucoadhesive polymers such as chitosan, carbopol, and gelatin. More advanced still are stimuli-responsive microsponges which release their payload in response to pH, temperature, enzyme activity, or redox gradients. These intelligent systems are particularly promising for tumor microenvironments, where acidic pH or overexpressed enzymes can trigger site-specific release.Research has demonstrated effective delivery of anti-inflammatory and chemotherapeutic agents through such environment-sensitive designs [80].

10.4. Scope in Vaccine Delivery and Oncology

Microsponges possess significant potential in vaccine delivery, particularly in oral, dermal, and mucosal immunization platforms. Their porous architecture facilitates sustained antigen release, and their surface can be engineered for adjuvant conjugation to enhance immune responses. This non-invasive vaccine delivery strategy can improve patient compliance and enable controlled immune stimulation.In oncology, microsponges are being studied for their capacity to deliver chemotherapeutics with high local concentrations, minimizing systemic toxicity. Moreover, dual-drug loading (e.g., chemotherapeutic + resistance modulator) is now feasible, offering solutions against multi-drug resistance (MDR) in cancers [81].

CONCLUSION

Microsponge Drug Delivery Systems (MDDS) have emerged as an innovative and adaptable platform that addresses many limitations associated with conventional drug delivery methods. By leveraging their unique porous architecture, MDDS offer remarkable benefits such as enhanced drug stability, controlled release kinetics, and improved site-specific targeting, thereby contributing significantly to therapeutic efficacy and patient compliance. Throughout the reviewed document, it is evident that the microsponge system has successfully transitioned from cosmetic and dermatological applications to systemic and targeted drug delivery, supported by advancements in polymer science, formulation techniques, and characterization tools.Despite the progress, certain challenges persist—particularly in large-scale manufacturing, regulatory standardization, and reproducibility. Addressing these constraints is essential to enable broader clinical acceptance and commercial viability. Encouragingly, recent developments indicate a transformative trajectory for MDDS, fueled by integration with nanotechnology, which enables enhanced cellular uptake and barrier penetration. Moreover, the adaptation of these systems for personalized medicine holds great promise, allowing for patient-specific drug regimens based on genetic and phenotypic profiles. Future-focused innovations such as bioadhesive and stimuli-responsive microsponges further elevate the potential of MDDS in complex therapeutic areas like oncology and vaccine delivery. These smart systems can respond to physiological triggers (pH, temperature, enzymes), enabling controlled and environment-specific drug release. Thus, the microsponge technology stands at the cusp of redefining modern drug delivery—offering a modular, scalable, and intelligent system capable of revolutionizing both chronic and acute treatment paradigms.By fostering multidisciplinary collaboration and refining regulatory frameworks, MDDS could become a mainstay in next-generation pharmaceutics.

REFERENCES

1. Langer R. Drug delivery and targeting. Nature. 1998 May 1;392(6679).
2. Allen TM, Cullis PR. Drug delivery systems: entering the mainstream. Science. 2004 Mar 19;303(5665):1818-22.
3. Nagarsenker MS, Jain AS, Shah SM. Functionalized lipid particulates in targeted drug delivery. InTargeted Drug Delivery: Concepts and Design 2014 Nov 5 (pp. 411-431). Cham: Springer International Publishing.
4. Siepmann J, Siepmann F. Modeling of diffusion controlled drug delivery. Journal of controlled release. 2012 Jul 20;161(2):351-62.
5. Rawat M, Singh D, Saraf S, Saraf S. Nanocarriers: promising vehicle for bioactive drugs. *Biol Pharm Bull*. 2006;29(9):1790–8. https://doi.org/10.1248/bpb.29.1790
6. Nacht S, Katz M. The microsponge: a novel topical programmable delivery system. In: *Topical Drug Delivery Formulations*. 1990. p. 299–325.
7. D'souza JI, More HN. Topical anti-inflammatory gels of fluocinolone acetonide entrapped in eudragit-based microsponges. *Res J Pharm Technol*. 2008;1(4):502–6.
8. Chadawar V, Shaji J. Microsponge delivery system. *Current Drug Delivery*. 2007;4(2):123–9. https://doi.org/10.2174/156720107780598424
9. Won R. Method for delivering an active ingredient by controlled time release utilizing a novel delivery vehicle which can be prepared by a process utilizing the active ingredient as a porogen. US Patent 4690825A; 1987.
10. Embil K, Nacht S. The microsponge delivery system (MDS): a topical delivery system with reduced irritancy incorporating multiple triggering mechanisms for the release of actives. *J Microencapsul*. 1996;13(5):575–88. https://doi.org/10.3109/02652049609026069
11. Jelvehgari M, Siahi MR, Azarmi S, Martin GP, Nokhodchi A. The microsponge delivery system of benzoyl peroxide: preparation, characterization and release studies. *Int J Pharm*. 2006;308(1–2):124–32. https://doi.org/10.1016/j.ijpharm.2005.11.014
12. Orlu M, Cevher E, Araman A. Design and evaluation of colon-specific drug delivery system containing flurbiprofen microsponges. *Int J Pharm*. 2006;318(1–2):103–17. https://doi.org/10.1016/j.ijpharm.2006.03.042

13. Ravi G, Ravi V, Bose PSC, Saritha D. Microsponges – A comprehensive review: success and challenges. Int J Adv Pharm Res. 2019. Available from: https://iajpr.com/iajprfiles/uploaddir/190604.

14. Jadhav N, Patel V, Mungekar S, Bhamare G. Microsponge delivery system: an updated review, current status and future prospects. J Sci Ind Res. 2013. Available from: http://www.jsirjournal.com/Vol2Issue6019.

15. Kumar S, Tyagi LK, Singh D. Microsponge delivery system (MDS): A unique technology for delivery of active ingredients. Int J Pharm Sci Res. 2011.https://www.researchgate.net/publication/220048876

16. Mandal S, Bhumika K, Kumar M, Hak J. A novel approach on microsponges drug delivery system: method of preparations, application, and its future prospective. Indian J Pharm Educ Res. 2024;58(1):45–54. Available from: https://www.ijper.org/sites/default/files/IndJPhaEdRes-58-1-45.pdf

17. Padhi RK, Ahmed F. Advances in microsponge technology: a comprehensive review. Res J Pharm Life Sci. 2024;5(2):12–19. Available from: https://www.rjpls.org/documents/2024/v5-i2-03.pdf

18. Halder S, Behera US, Poddar S, Khanam J. Preparation of Microsponge Drug Delivery System (MSDDS) followed by a scale-up approach. AAPS PharmSciTech. 2024. Available from: https://link.springer.com/article/10.1208/s12249-024-02874-y

19. Chadawar V, Shaji J. Microsponge delivery system. Curr Drug Deliv. 2007;4(2):123–9.

20. Rathi R, Chopra H, Kaur M. Advancements in microsponges for the management of vaginal and colorectal diseases: a comprehensive review. Appl Chem Eng. 2024. Available from: https://www.researchgate.net/publication/380214625

21. Alburyhi MM, Yahya TAA, Saif AA. Formulation and evaluation of lornoxicam microsponge-based gel as a transdermal drug delivery system. Int J Pharm Clin Res. 2025.

22. Jadhav N, Patel V, Mungekar S, et al. Microsponge delivery system: an updated review, current status and future prospects. *J Sci Ind Res*. 2013;2(6):19.

23. Padhi RK, Ahmed F. Advances in microsponge technology: a comprehensive review. *Res J Pharm Life Sci*. 2024;5(2):10–16.

24. Alburyhi MM, Yahya TAA, Saif AA. Formulation and evaluation of lornoxicam microsponge-based gel as a transdermal drug delivery system. *Int J Pharm Sci*. 2025.
25. Shukla A, Garg A, Garg S. Application of microsponge technique in topical drug delivery system. *Asian J Biomater Res*. 2016;2(2):8–14.
26. Ravi G, Ravi V, Bose PSC, Saritha D. Microsponges – a comprehensive review: success and challenges. *Int J Adv Pharm Res*. 2019;10(4):134–141.
27. Patel UB, Patel HM, Shah CN, Barse R. A review - recent research on microsponge: a novel new drug delivery system. *Int J Adv Pharm*. 2018;6(3):45–51.
28. Halder S, Behera US, Poddar S, Khanam J. Preparation of microsponge drug delivery system followed by a scale-up approach. *AAPS PharmSciTech*. 2024.
29. Junqueira MV, Bruschi ML. A review about the drug delivery from microsponges. *AAPS PharmSciTech*. 2018;19(6):2061–2070. doi:10.1208/s12249-018-0976-5
30. Vyas SP, Khar RK. Targeted and Controlled Drug Delivery: Novel Carrier Systems. 1st ed. New Delhi: CBS Publishers; 2002. p. 417-26.
31. Kaur IP, Rana C, Singh H. Development of controlled release microsponges of betamethasone and salicylic acid for topical use. Indian J Pharm Sci. 2010;72(2):223–9. doi:10.4103/0250-474X.65013
32. Thakur R, Kashyap N, Bharti SK, Kumar S. Formulation and evaluation of microsponges for topical drug delivery of mupirocin. Asian J Pharm Clin Res. 2016;9(5):85–90.
33. Chadawar V, Shaji J. Microsponge delivery system. Curr Drug Deliv. 2007;4(2):123–9. doi:10.2174/156720107780866106
34. Jelvehgari M, Siahi MR, Azarmi S, Nokhodchi A. The microsponge delivery system of benzoyl peroxide: Preparation, characterization and release studies. Int J Pharm. 2006;308(1-2):124–32. doi:10.1016/j.ijpharm.2005.11.009
35. D'souza JI, More HN. Topical anti-inflammatory gels of fluocinolone acetonide entrapped in eudragit based microsponge delivery system. Res J Pharm Technol. 2008;1(4):502–6.
36. Yadav N, Deshmukh R. In silico modeling, formulation, optimization, and in-vitro evaluation of candidone microsponges. J Appl Pharm Sci. 2024.
37. Osmani RAM, Aloorkar NH, Thaware BU, et al. Microsponge based drug delivery system for gastroparesis. J Pharm Bioallied Sci. 2015;7(1):49–56.

38. Mahmoud DBED, Shukr MH, ElMeshad AN. Gastroretentive microsponge of mitiglinide calcium. AAPS PharmSciTech. 2018;19(7):2974–2989.

39. Behera US, Halder S, Poddar S, Khanam J. Preparation of Microsponge DDS Followed by Scale-Up. AAPS PharmSciTech. 2024.

40. Khattab A, Nattouf A. Optimization of clindamycin entrapment in microsponge gel. Sci Rep. 2021;11:23475.

41. Mohan D, Gupta VRM. Microsponge based drug delivery system of voriconazole for fungal infection: formulation development and In-vitro evaluation. J Drug Deliv Ther. 2019.

42. Jadhav P, Dombe S, Yadav V, et al. Formulation and evaluation of microsponge gel for topical delivery of antifungal drug. Int J App Pharm. 2017;9(4):15–22.

43. Orlu M, Cevher E, Araman A. Design and evaluation of colon-specific drug delivery system containing flurbiprofen microsponges. Int J Pharm. 2006;318(1-2):103-117.

44. Alburyhi MM, Yahya TAA, Saif AA. Formulation and Evaluation of Lornoxicam Microsponge-Based Gel. Int J Pharm Sci Res. 2025.

45. Jelvehgari M, Siahi-Shadbad MR, Azarmi S, et al. The microsponge delivery system of benzoyl peroxide: Preparation, characterization and release studies. Int J Pharm. 2006;308(1–2):124-132.

46. Bhatia M, Saini M. Formulation and evaluation of curcumin microsponges for oral and topical drug delivery. Prog Biomater. 2018;7:239–248.

47. Pande VV, Kadnor NA, Kadam RN. Fabrication and characterization of sertaconazole nitrate microsponge as a topical drug delivery system. Int J Pharm Sci. 2015;77(4):675-681.

48. Osmani RAM, Aloorkar NH, Thaware BU, et al. Microsponge based drug delivery system for augmented gastroparesis therapy. J Appl Pharm Sci. 2015;5(9):76–81.

49. Singh R, Jain V. Design and characterization of colon-specific drug delivery system containing paracetamol microsponges. Arch Pharm Res. 2011;34(1):167-175. DOI

50. Moin A, Deb TK, Osmani RAM, et al. Fabrication, characterization, and evaluation of microsponge delivery system for fungal therapy. J Basic Clin Pharm. 2016;7(1):39–44. PMC

51. Arya P, Pathak K. Assessing the viability of microsponges as gastro retentive drug delivery system of curcumin. Int J Pharm. 2014;460(1–2):1–12. DOI

52. Nief RA, Hussein AA. Preparation and evaluation of meloxicam microsponges as transdermal delivery system. Iraqi J Pharm Sci. 2014.

53. Shukla A, Garg A, Garg S. Application of Microsponge Technique in Topical Drug Delivery System. Asian J Biomater Res. 2016.

54. Ma L, Guo S, Piao J, Piao M. Preparation and evaluation of a microsponge dermal stratum corneum retention drug delivery system for griseofulvin. AAPS PharmSciTech. 2022.

55. Mandal S, Bhumika K, Kumar M, Hak J. A novel approach on microsponges drug delivery system: method of preparations, application, and its future prospective. Indian J Pharm Educ Res. 2024;58(1):45-54.

56. Alburyhi MM, Yahya TAA, Saif AA. Formulation and evaluation of lornoxicam microsponge-based gel as a transdermal drug delivery system. 2025.

57. Ravi G, Ravi V, Bose PSC, Saritha D. Microsponges – A comprehensive review: Success and challenges. Int J Pharm Res. 2019.

58. Biharee A, Bhartiya S, Yadav A. Microsponges as drug delivery system: past, present, and future perspectives. Curr Pharm Des. 2023.

59. Padhi RK, Ahmed F. Advances in Microsponge Technology: A Comprehensive Review. Res J Pharm Life Sci. 2024. Available from: https://www.rjpls.org/documents/2024/v5-i2-03.

60. Rathi R, Kaur S, Chopra H, Kaur M. Advancements in microsponges for the management of vaginal and colorectal diseases: A comprehensive review. Appl Chem Eng. 2024.

61. Junqueira MV, Bruschi ML. A review about the drug delivery from microsponges. AAPS PharmSciTech. 2018.

62. Jadhav N, Patel V, Mungekar S, Bhamare G. Microsponge delivery system: an updated review, current status and future prospects. J Sci Ind Res. 2013.

63. Sharma S, Kaur M, Kaur S. Microsponge Technology as a Novel Approach for Topical Drug Delivery: An Acquainted Review. IOSR J Pharm Biol Sci. 2020. https://www.academia.edu/download/64683472/A1505030113

64. Pawashe SL, Nagesh C, Mohite AR. Review on Microsponges. World Journal of Pharmaceutical Research. 2024. https://wjpr.s3.ap-south-1.amazonaws.com/article_issue/b5c52a514acc4dd54191374685ed003c.

65. Kumari A, Jain A, Hurkat P, Verma A. Microsponges: A Pioneering Tool for Biomedical Applications. Crit Rev Ther Drug Carrier Syst. 2016;33(1):1-22. https://www.dl.begellhouse.com/journals/3667c4ae6e8fd136,7625a1812630d890,744bfabb4008b678.html

66. Osmani RA, Aloorkar NH, Kulkarni AS. A New Cornucopia in Topical Drug Delivery: Microsponge Technology. Asian J Pharm Sci. 2014. https://www.academia.edu/download/78931840/A_NEW_CORNUCOPIA_IN_TOPICAL_DRUG_DELIVER20220116-11412-jvbfm7.

67. Pandey P, Purohit D, Dureja H. Nanosponges–A Promising Novel Drug Delivery System. Recent Patents on Nanotechnology. 2018;12(3):205–212. https://www.ingentaconnect.com/content/ben/nanotec/2018/00000012/00000003/art00004

68. Nandi S, Karati D, Mukherjee S. Nanosponges–Road Less Explored Changing Drug Delivery Approach: An Explicative Review. Curr Pharm Biotechnol. 2025. https://www.ingentaconnect.com/content/ben/cpb/pre-prints/content-bms-cpb-2024-69

69. Srivastava R. Microsponges for Drug Delivery. In: Drug Delivery: An Integrated Clinical and Engineering Approach. CRC Press; 2017. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315117584-10/microsponges-drug-delivery-rishabh-srivastava

70. Kandekar U, Pujari R, Munot N, Chorge T. Nanosponges–Versatile Platform as Drug Carrier. Recent Patents on Nanotechnology. 2023. https://www.researchgate.net/publication/363308189_Nanosponges-_Versatile_platform_as_drug_carrier

71. Mullick P, Hegde AR, Gopalan D. Nanosponges for Effective Skin Delivery of Drugs. Current Pharmaceutical Design. 2022;28(19):2183–2195. https://www.benthamdirect.com/content/journals/cpd/10.2174/1381612828666220518090431

72. Qureshi S, Alavi SE, Mohammed Y. Microsponges: Development, Characterization, and Physicochemical Properties. Assay Drug Dev Technol. 2024. https://www.liebertpub.com/doi/abs/10.1089/adt.2023.052

73. Won R. Method for delivering an active ingredient by controlled time release utilizing a novel delivery vehicle. US Patent No. 4690825. 1987.

74. Mahato RK, Singh M, Pathak H, Gogoi NR. Emerging Nanotechnology-Backed Formulations for the Management of Atopic Dermatitis. Ther Deliv. 2023;14(5):245–259. https://www.tandfonline.com/doi/full/10.4155/tde-2023-0033

75. Halder S, Behera US, Poddar S, Khanam J. Preparation of Microsponge Drug Delivery System (MSDDS) Followed by a Scale-Up Approach. AAPS PharmSciTech. 2024. Available from: https://link.springer.com/article/10.1208/s12249-024-02874-y

76. Junqueira MV, Bruschi ML. A review about the drug delivery from microsponges. AAPS PharmSciTech. 2018;19(5):1501–1510.

77. Padhi RK, Ahmed F. Advances in microsponge technology: A comprehensive review. Res J Pharm Life Sci. 2024;5(2):13–22.

78. Rathi R, Kaur S, Chopra H, Kaur M. Advancements in microsponges for the management of vaginal and colorectal diseases: A comprehensive review. Applied Chemical Science International. 2024.

79. Ravi G, Ravi V, Bose PSC, Saritha D. Microsponges – A Comprehensive Review: Success and Challenges. Int J Adv Pharm Res. 2019. Available from: https://iajpr.com/iajprfiles/uploaddir/190604_DOI.

80. Kumar S, Tyagi LK, Singh D. Microsponge delivery system (MDS): A unique technology for delivery of active ingredients. Int J Pharm Sci Res. 2011;2(5):3069–3080.

81. Patel HM, Shah CN. A review: Recent research on microsponge—a novel new drug delivery system. Int J Adv Pharm. 2018.