RESEARCH PAPER

Microsponge Drug Delivery Systems: An Analytical Review of Formulation, Evaluation, And Therapeutic Applications

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Abstract
Microsponge drug delivery systems are porous, polymeric microspheres designed to entrap active agents and release them in a controlled and sustained manner. Owing to their high porosity, tunable particle size, and compatibility with diverse polymers, microsponges have emerged as versatile carriers for both pharmaceutical and cosmetic applications. This review provides an analytical overview of microsponge technology covering classification, historical development, formulation strategies, characterization parameters, drug-release mechanisms, and therapeutic applications. Preparation methods such as liquid–liquid suspension polymerization and quasi-emulsion solvent diffusion are discussed alongside the influence of polymer selection (e.g., ethyl cellulose, PMMA, Eudragit, PLGA) on entrapment efficiency and release behavior. Critical evaluation techniques—including particle size analysis, surface morphology, porosity assessment, entrapment efficiency, and kinetic modeling using zero-order, Higuchi, and Korsmeyer–Peppas equations—are summarized to link formulation variables with performance outcomes. Comparative analysis highlights advantages of microsponges over conventional carriers, particularly for topical and transdermal delivery where reduced irritation, improved stability, and prolonged action are desirable. Evidence from recent studies demonstrates successful incorporation of microsponges into gels, creams, patches, and oral systems for antifungal, anti-acne, anti-inflammatory, and sunscreen applications. The review also examines emerging research trends, recent patents, and the translation of microsponge technology into commercial products such as benzoyl peroxide and tretinoin microsponge formulations. Key challenges, including scale-up, residual solvents, regulatory complexity, and limited exploration in biologics delivery, are critically discussed. Future directions emphasize biodegradable polymers, stimulus-responsive systems, and expanded therapeutic scope. Overall, microsponge systems represent a promising platform for controlled drug delivery with significant potential across dermatology, oral therapy, transdermal systems, oncology, and cosmetic science.

Keywords: Microsponge drug delivery; Controlled release; Quasi-emulsion solvent diffusion; Polymeric porous microspheres; Topical and transdermal delivery; Drug release kinetics
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Introduction

Microsponges are miniature, porous polymeric particles that are intended to hold and release active substances (such medications or cosmetic elements) gradually over an extended period of time. These particles can be utilized safely in a range of formulations since they are usually composed of biocompatible and biodegradable components. Because of their special porous structure, they may contain large amounts of active substances in their microscopic holes, which can then be released gradually in response to certain circumstances, such as variations in moisture, pH, or temperature [1].

Microsponges work on the principle of controlled release technology. Microsponges offer a continuous release, which lowers the frequency of administration or dose, in contrast to traditional drug delivery methods that may release an active component all at once or over a brief period of time. Better patient or customer compliance as well as more constant treatment benefits may result from this.

Porous Structure: The microsponges may capture and retain medications or substances thanks to their network of tiny holes. The rate at which the active chemicals are released can be affected by the size of the pores. Synthetic polymers like polymethyl methacrylate (PMMA) and biodegradable ones like

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poly (lactic-co-glycolic acid) (PLGA) are frequently utilized to make microsponges. These substances are selected because of their effective chemical encapsulation and safe degradation over time. Microsponges are tiny enough to be used in topical and systemic drug delivery systems, typically ranging in size from 1 to 100 microns [2].

Classification of Microsponges

Microsponges can be systematically classified based on the nature of polymer employed, method of preparation, route of drug delivery, and mechanism of drug release. Based on polymer type, microsponges are broadly categorized into hydrophobic polymer-based systems such as ethyl cellulose and polymethyl methacrylate, biodegradable polymer-based systems such as poly (lactic-co-glycolic acid), and pH-responsive polymer systems such as Eudragit derivatives. Depending on the preparation technique, microsponges are commonly prepared by liquid-liquid suspension polymerization and quasi-emulsion solvent diffusion methods. From the application perspective, these are used in topical, oral, transdermal, colon-targeted, and vaginal drug delivery systems. Based on drug release behavior, they may exhibit diffusion-controlled, erosion-controlled, or combined release mechanisms. This systematic classification provides a better understanding of their versatility and formulation adaptability in modern drug delivery.

Historical Development of Microsponge Systems in Pharmaceutical and Cosmetic Formulations

Microsponge systems were first developed in the early 1980s when researchers started looking at novel approaches to sustained and regulated drug delivery [3]. This cutting-edge technique was developed to address some of the drawbacks of conventional drug delivery methods, including their quick release, brief duration of action, and adverse effects brought on by high peak drug concentrations. Microsponge technology began as an experimental concept in controlled-release medication administration in the 1980s and has since developed into a flexible and popular platform in the cosmetics and pharmaceutical sectors. It has transformed the formulation and use of medications and cosmetics, improving medical care and consumer goods, thanks to its capacity to deliver active chemicals gradually and effectively [4]. As technology develops toward more accurate, sustainable, and customized distribution methods, microsponge systems have a bright future.

Importance of Microsponge Technology in Drug Delivery

Modern medications and therapies now place a high priority on the necessity of long-term, regulated drug delivery. Rapid drug release, changing drug concentrations, and frequent dosing are some of the issues that traditional drug delivery systems frequently confront. These restrictions may result in worse side effects, less efficacy, and noncompliance from patients [5]. Microsponges provide a useful remedy for these problems because of their exceptional capacity to encapsulate active pharmacological ingredients (APIs) and release them gradually. Here's why **microsponge technology** has become so important in drug delivery:

a.Sustained Release for Consistent Therapeutic Effect

The abilities of microsponges to provide a drug's continuous release over a prolonged period of time are one of their main benefits. This is especially important for medications whose therapeutic benefits depend on constant plasma concentrations [6]. Conventional medication formulations frequently produce a sharp rise in concentration followed by a sharp fall, which may result in less-than-ideal therapeutic levels during the troughs. Microsponges, on the other hand, release the active component gradually, guaranteeing continuous, regulated release over time. This might lead to the need for frequent dosage and an increased risk of adverse effects when the medication concentration is too high. This keeps the body's medication levels steady and eliminates the need for repeated doses, which can greatly increase patient compliance, particularly for long-term diseases like diabetes, hypertension, or chronic pain. In recent year many research have been found advantages of microsponges for Sustained Release for Consistent Therapeutic Effect such as Salah et al,. 2018 conclude that, This study successfully developed a novel miconazole (MCZ) microsponge-based vaginal gel to address the limitations of traditional azole formulations, such as poor retention and irritation. By optimizing formulation factors, the microsponges achieved high entrapment efficiency, controlled drug release, and favorable physicochemical properties. Incorporation into Carbopol gel enhanced bioadhesion and mucosal retention. The optimized formulation demonstrated superior in vivo antifungal efficacy compared to the market product, suggesting improved therapeutic outcomes and patient compliance in vaginal candidiasis treatment [7].

b. Reducing Adverse Reactions

Conventional delivery methods' rapid drug release can cause concentration spikes, which can be harmful or have unfavorable consequences. Because microsponges release the drug gradually and predictably, they reduce the chance of these fluctuations, which is especially problematic for medications with a narrow therapeutic window where even slight changes in concentration can cause harmful side effects or ineffectiveness. Microsponges can reduce side effects and improve a medicine's overall safety profile by regulating the amount of the drug that is accessible at any one moment [8].

c. Enhanced Absorption and Bioavailability

Additionally, microsponges can increase the bioavailability of medications that are unstable or poorly soluble. For example, when taken orally, medications with poor solubility could not be properly absorbed in the digestive system. The active ingredient in these medications can be shielded from deterioration and more efficiently transported to the site of

absorption by encapsulating them in microsponges. Furthermore, by making hydrophobic medications more soluble, microsponges can increase their absorption and bioavailability [9]. This is particularly crucial for medications that need targeted release in particular gastrointestinal tract regions or that have a low oral bioavailability. In recent year many research have been found advantages of microsponges for enhancement of absorption and bioavailability such as Abdalla et al,. 2021 research that, This study highlights the potential of microsponges as a promising approach to overcome the variable oral bioavailability of carbamazepine (CBZ) caused by its transformation into a less soluble form. By optimizing polymer composition using a quasi-emulsion solvent diffusion technique, microsponges achieved improved encapsulation, controlled drug release, and enhanced oral absorption. The optimized formulation showed a 2.6-fold increase in bioavailability, confirming microsponges as effective carriers for sustained oral delivery of CBZ [10].

d. Targeted administration of drugs

Microsponges offer a promising approach for targeted drug delivery due to their ability to encapsulate medications and control their release, making them especially valuable in treatments that require localized action, such as topical infections and cancer therapy. In dermatological applications, microsponges can deliver drugs like retinoids, antibiotics, or anti-inflammatory agents directly to the skin, ensuring localized therapeutic effects without impacting the rest of the body. By modulating the timing and mechanism of drug release, they also help reduce irritation often associated with conventional topical formulations. In cancer therapy, microsponges are being explored for their potential to deliver chemotherapeutic drugs directly to tumor sites, thereby minimizing systemic toxicity and enhancing treatment efficacy [11]. This targeted delivery approach significantly reduces the adverse side effects commonly experienced with traditional chemotherapy, as it spares healthy tissues from unnecessary drug exposure.

e. Compliance and Convenience

The prolonged and controlled release of medications from microsponges can significantly reduce dosing frequency, which in turn enhances patient compliance—an essential factor in the effective management of chronic conditions. Diseases such as diabetes, hypertension, and mental health disorders often require medications to be taken daily or multiple times a day, leading to high rates of non-adherence. By incorporating microsponges into treatment regimens, patients may only need to take their medication once a day or even less frequently, improving adherence and ultimately leading to better health outcomes [12]. Furthermore, microsponges can be easily integrated into familiar dosage forms like tablets, creams, ointments, or patches, making them more accessible and acceptable to patients [13]. This versatility not only increases patient comfort and convenience but also encourages consistent use of prescribed therapies.

f. Reduced Irritation and Increased Safety for Topical Uses

Microsponges are useful because topical treatments reduce irritation, which is an ordinary problem with many active chemicals, including retinoids, anti-aging compounds, and anti-acne therapies. When used in high doses, these chemicals frequently result in dry or red skin.

The active components are supplied in smaller, more manageable dosages over time thanks to the progressive release that microsponges offer. This increases the efficacy of the active substances without irritating the skin and also improves skin safety [14].

g.Resolving Challenges in Hard-to-Deliver Pharmaceuticals drugs

Some medications, especially biologics (such as insulin or monoclonal antibodies), have difficulties with delivery because of their instability or huge molecular size. In order to increase the effectiveness and bioavailability of these hard-to-deliver medications, microsponges are being investigated as a possible encapsulation and stabilization method [15].

Advantages of Microsponges

Microsponges provide a number of unique benefits when it comes to medication administration, chief among them being the regulated and prolonged release of active substances [16]. These advantages are particularly important for improving treatment results and reducing side effects. The following are the main benefits of employing microsponges:

a. Diminished Adverse Reactions

The potential of microsponges to lessen adverse effects linked to high concentrations of active substances is one of its most important benefits. Drugs that are delivered gradually over time maintain lower peak plasma concentrations, which reduces the likelihood of dose-dependent adverse effects [17]. This is especially helpful for medications that might have negative side effects when taken in large quantities.

b. Improved Stability

Compared to their free equivalents, drugs encapsulated in microsponges are frequently more stable. By acting as a barrier, the microsponge matrix protects the medication from elements like light, oxygen, and moisture that might break down the active component [18]. The drug's chemical stability and shelf life are improved by this protection.

c. Increased Adherence by Patients

Patients don't need to take as many dosages throughout the day when a medication may be delivered consistently and continuously over time [19]. This lessens how frequently medications are administered, which is particularly crucial for managing long-term disorders or chronic diseases.

d. Reduced Irritation in Topical Uses

Reducing skin irritation and sensitivity is a major difficulty for topical drug administration, particularly when employing powerful medications like antibiotics, retinoids, or anti-inflammatory medicines. Because they provide a regulated release that reduces direct, high-concentration skin exposure, microsponges are excellent in this regard.

The composition and structure of microsponges

The composition and structure of microsponges play a crucial role in determining their performance in drug delivery systems. Typically composed of various polymeric materials, microsponges are designed to encapsulate active ingredients and provide desired release profiles, such as sustained, controlled, or targeted release. The choice of material is particularly important, as it directly affects the microsponge's stability, biocompatibility, release rate, and degradation behavior. Among the most commonly used materials is ethyl cellulose (EC)**,** [20] a synthetic polymer derived through the ethylation of cellulose, valued for its excellent film-forming abilities and controlled-release properties. Another widely used material is polymethyl methacrylate (PMMA)**,** known for its rigidity, transparency, mechanical strength, and biocompatibility, which allows it to form porous microspheres suitable for encapsulating a wide range of active compounds [21]. Poly(lactic-co-glycolic acid) (PLGA)**,** a biodegradable copolymer of lactic and glycolic acids, is also favored in pharmaceutical applications due to its ability to degrade into non-toxic byproducts within the body. In addition, other biodegradable polymers are utilized to enable prolonged drug delivery, reducing the need for frequent dosing and ensuring a consistent release of the active ingredient while leaving no harmful residues after degradation [22]. These carefully selected materials collectively ensure the structural integrity and functionality of microsponges in therapeutic applications.

Particle Size and Porosity

The mechanical strength, drug release characteristics, and encapsulation capacity of microsponges are significantly influenced by two key factors: particle size and porosity [23]. These properties govern how microsponges regulate the release of encapsulated drugs or active ingredients and how they interact with their surrounding environment, such as bodily fluids or skin. Typically, the particle size of microsponges ranges from 1 to 100 microns, depending on the formulation and intended use. Particle size plays a crucial role in several aspects [24]. For instance, encapsulation efficiency is often higher in smaller microsponges due to their larger surface area, though this can also lead to a faster drug release. The drug release rate is closely tied to size as well—smaller particles tend to release drugs more rapidly due to a higher surface area-to-volume ratio, whereas larger particles enable slower, more sustained release [25]. Additionally, the appropriate particle size varies with the route of administration: topical treatments generally use microsponges sized between 5 and 50 microns to ensure gradual release on the skin's surface, while injectable or oral formulations may require different size specifications for optimal effectiveness. Porosity, defined by pore volume and surface area, is equally critical [26]. The presence of microscopic pores or cavities determines both the storage capacity of active ingredients within the microsponges and the rate at which these substances are released upon contact with the target environment. Thus, both particle size and porosity are essential in designing effective microsponge-based drug delivery systems.

Commonly used Polymers in microsponge preparation

The selection of polymer plays a decisive role in determining the structural integrity, drug loading capacity, and release characteristics of microsponges. Hydrophobic polymers such as ethyl cellulose and polymethyl methacrylate are widely used for sustained and controlled release applications. Eudragit RS100 and RL100 are preferred for pH-independent controlled release formulations. Biodegradable polymers such as PLGA and PLA are increasingly used for long-term and safe drug delivery. Polyvinyl alcohol is often used as a stabilizer and emulsifier during preparation. The choice of polymer is therefore dictated by the physicochemical properties of the drug and the intended route of administration.

Procedures for Producing Microsponges

Liquid-liquid polymerization in suspension

Monomers and the functional or active components, which are immiscible with water, are often used to create a solution. After that, this phase is rapidly suspended in an aqueous phase, which often contains additives like dispersants and surfactants to aid in suspension [27]. Activating the monomers by catalysis, raising the temperature, or irradiating them is how polymerization is accomplished after the solution has distinct droplets of the appropriate size. A spherical structure with thousands of microsponges grouped together like grapes, creating interconnected reservoirs, is created as the polymerization process proceeds [28, 29]. [Figure 1].

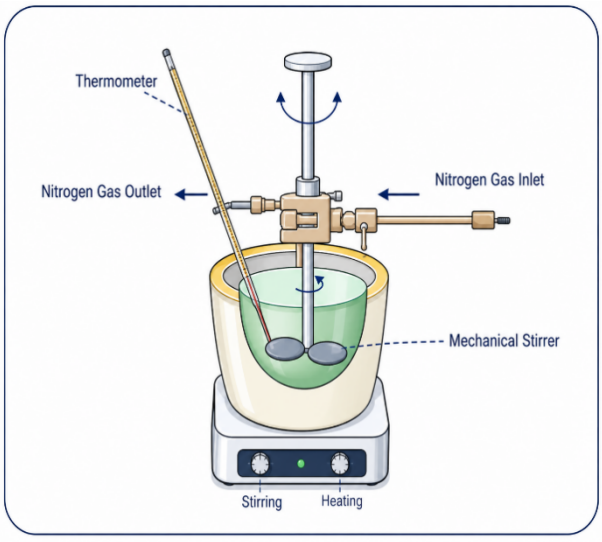

Fig 1: Reaction vessel for micro sponge preparation by liquid-liquid suspension polymerization

After the polymerization process is finished, the solid particles that are produced are extracted from the suspension, cleaned, and processed until they are

essentially ready for use. Starting materials for the microsponge products can be either methyl methacrylate and ethylene glycol dimethacrylate or styrene and divinylbenzene [30].

Quasi-emulsion solvent diffusion

The inner organic phase is made by disintegrating Eudragit RS 100 in ethyl alcohol, then adding the drug to the mixture and ultrasonically dissolving it at 35°C. The inner phase is then poured into the polyvinyl alcohol solution in water (the outer phase), and after stirring for 60 minutes, the mixture is filtered to separate the microsponges, which are then dried in an air-heated oven at 40°C for 12 hours [31,32]. [Figure 2]

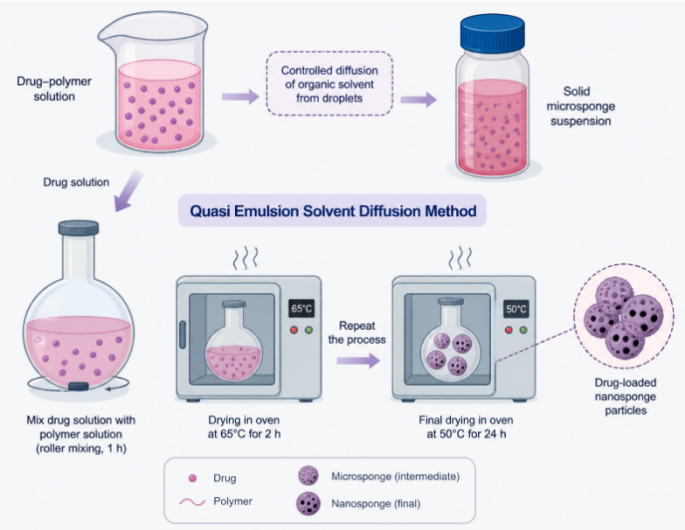

Fig 2: Preparation of microsponges by the quasi-emulsion solvent diffusion method

Ingredients can be post-loaded after the microsphere structure has been pre-formed, or they can be confined in microsponge polymers during synthesis if they are too labile to tolerate the conditions of polymerization. Since most medicinal and cosmetics chemical substances would break down at the temperatures used for polymerization, the latter method is usually the one that is recommended [33, 34].

Characterization and Evaluation of Microsponges

Proper characterization of microsponges is essential to ensure reproducibility, performance, and therapeutic efficacy. Particle size analysis is typically performed using optical microscopy or laser diffraction methods, as particle size directly influences drug release rate and skin deposition. Surface morphology and porosity are evaluated using scanning electron microscopy, which confirms the presence of a porous architecture responsible for drug entrapment. Entrapment efficiency and production yield are calculated to assess formulation efficiency. In-vitro drug release studies are conducted using dissolution apparatus or Franz diffusion cells, and the data are fitted into kinetic models such as zero-order, Higuchi, and Korsmeyer-Peppas models to understand the release mechanism. Stability studies under varying temperature and humidity conditions are also performed to ensure the integrity of the microsponge system during storage.

Drug release data from microsponge formulations are commonly fitted into kinetic models to understand the mechanism of release. Zero-order kinetics indicates constant drug release over time, whereas the Higuchi model explains diffusion-controlled release from porous matrices. The Korsmeyer-Peppas model is widely used to determine whether the release follows Fickian diffusion or anomalous transport. Such kinetic modeling is essential for predicting microsponge performance.

Drug Release Mechanisms

One of the key advantages of microsponges is their ability to provide controlled and sustained release of encapsulated drugs. Their porous structure allows them to act as reservoirs, gradually dispensing active ingredients over time without the need for frequent dosing. This continuous release helps maintain stable therapeutic drug levels in the body, enhancing treatment effectiveness, especially for chronic conditions [35]. The controlled release mechanism is primarily driven by two processes: diffusion and erosion. Diffusion involves the movement of the drug from the microsponge's interior through its porous matrix into the surrounding environment, guided by concentration gradients [36]. Erosion, on the other hand, occurs when the polymer matrix slowly degrades, releasing the drug in the process. This dual mechanism enables precise regulation of drug delivery, making microsponges ideal for managing long-term conditions like diabetes, hypertension, and chronic pain, as well as for topical therapies that require prolonged, localized action [37].

Comparison of Microsponges with other drug delivery carriers

Microsponges offer distinct advantages over conventional carriers such as microspheres, liposomes, nanoparticles, and niosomes. Unlike microspheres, microsponges possess a highly porous structure

allowing higher drug loading and controlled release. Compared to liposomes and nanoparticles, microsponges exhibit superior stability and reduced risk of burst release. Their ability to minimize irritation makes them particularly suitable for topical applications. Furthermore, microsponges can be incorporated into various dosage forms without compromising formulation stability, making them more versatile than many nano-carriers.

Factors Influencing Microsponge Drug Release

The rate and extent of drug release from microsponges are governed by several key factors, including drug solubility, the type of polymer used, and external environmental conditions [38]. Drug solubility plays a crucial role; hydrophilic drugs tend to release more quickly in aqueous environments due to their high water solubility, especially when housed in highly porous microsponges. In contrast, lipophilic drugs release more slowly and may require modifications to the microsponge matrix or the addition of surfactants to enhance their solubility and release profile [39]. The polymer used in microsponge fabrication also significantly affects drug release dynamics [40]. Hydrophilic polymers, like polyvinyl alcohol, facilitate faster diffusion of water-soluble drugs, while hydrophobic polymers, such as PMMA and PLGA, provide a slower, more controlled release—ideal for prolonged therapy [41]. Biodegradable polymers like PLA and PLGA support extended drug release through gradual polymer breakdown. External conditions such as pH, temperature, ionic strength, and enzymatic activity further influence drug release [42]. For instance, varying pH levels across the gastrointestinal tract can be exploited for site-specific delivery, and temperature shifts can alter the solubility or structure of temperature-sensitive polymers, affecting release rates. Similarly, enzymes or specific ions present at target sites can trigger drug release, making microsponges highly adaptable for precise, condition-responsive drug delivery.

Zero-Order Release: A Steady, Constant Release Rate

Zero-order release is the ability of some microsponges to release the medication at a steady pace [43]. For medications that need constant plasma levels throughout time with little concentration variations, this is ideal. Zero-order release produces more stable therapeutic effects by ensuring that the medicine is accessible in the body at a constant rate during the course of therapy [44].

Applications in Drug Delivery

In the context of drug delivery, microsponges have shown incredible adaptability, allowing the regulated and prolonged release of active medicinal substances through a variety of administration methods [45]. They are perfect for use in oral, topical, transdermal, and cancer treatment applications because of their porosity nature and capacity to encapsulate a variety of pharmacological compounds. Some of the most popular and noteworthy uses are listed below:

a. Oral Drug Delivery

Microsponges offer significant advantages in oral drug delivery, particularly for medications that are sensitive to the acidic environment of the stomach or require targeted release in specific regions of the gastrointestinal tract [46]. By encapsulating drugs within microsponges, the active ingredients are protected from premature degradation, such as that caused by stomach acid, allowing them to reach the intestines intact. This protective barrier is especially beneficial for delicate compounds like proteins, enzymes, and certain antibiotics. Additionally, microsponges can be engineered to release drugs at specific pH levels or in response to certain enzymes, enabling targeted delivery within the GI tract [47]. Their ability to provide sustained drug release further enhances treatment by maintaining consistent therapeutic levels, reducing the frequency of dosing, and improving patient adherence—particularly in the case of long-term therapies involving hormones, pain relievers, or antibiotics.

b. Topical Drug Delivery

Microsponges are widely used in dermatology for the topical delivery of medications due to their ability to provide controlled and sustained release of active ingredients [48]. This makes them especially valuable in both pharmaceutical and cosmetic treatments where long-lasting effects are desired with minimal side effects. By gradually releasing compounds like retinoids or anti-inflammatory agents, microsponges help reduce skin irritation and allergic reactions often associated with higher or more frequent dosing. This slow-release mechanism also enhances treatment adherence by reducing the need for repeated applications, which is particularly beneficial for managing chronic skin conditions [49]. Furthermore, the consistent therapeutic action at the targeted site improves the overall efficacy of the treatment, making microsponges a reliable and patient-friendly option in dermatological care.

c. Transdermal Drug Delivery Systems

Microsponges integrated into transdermal drug delivery systems offer a highly effective method for controlled and sustained release of medications through the skin. Unlike oral administration, which often results in fluctuating drug levels, microsponge-based transdermal patches maintain consistent therapeutic concentrations over extended periods, such as hours or even days. This steady release is particularly beneficial for medications like nicotine, hormones, or pain relievers that require long-term dosing [50]. Additionally, transdermal delivery bypasses the liver's first-pass metabolism, enhancing drug bioavailability and ensuring more efficient absorption

into the bloodstream. These patches are also non-invasive and easy to use, making them a convenient and patient-friendly option for managing chronic conditions like hormone imbalances or aiding in smoking cessation through nicotine replacement therapy.

d. Cancer Therapy

One of the most promising applications of microsponges lies in targeted drug delivery for cancer therapy, where they can significantly enhance treatment efficacy while minimizing harmful side effects. Microsponges can be engineered to deliver chemotherapeutic drugs directly to tumors or cancer cells by incorporating targeting agents such as antibodies or ligands that bind specifically to receptors on malignant tissues [51]. This targeted approach ensures that the therapeutic agents concentrate at the tumor site, thereby reducing systemic exposure and minimizing common chemotherapy-related side effects like nausea, hair loss, and immune suppression. Additionally, microsponges offer controlled and sustained drug release, providing a consistent supply of the medication over extended periods [52]. This not only increases the effectiveness of the treatment but also reduces the need for frequent dosing, improving patient compliance and overall outcomes.

Cosmetic formulations

Beyond pharmaceuticals, microsponges have gained considerable importance in cosmetic science. They are extensively used in sunscreens for prolonged UV protection, in anti-acne products to reduce irritation from retinoids and benzoyl peroxide, in anti-aging creams for sustained release of active ingredients, and in skin-lightening formulations to improve stability of oxidation-prone agents such as arbutin. The controlled release property ensures prolonged cosmetic action with enhanced safety and consumer acceptability.

The use of microsponges in topical medication delivery systems has been the subject of much research in recent years. Numerous studies showing the potential and efficacy of microsponges for this purpose are highlighted in Table 1. Furthermore, Table 2 provides a summary of several instances of topical drug delivery microspheres and their particular uses. These developments demonstrate the increasing interest in and bright future of delivery methods based on microsponge and microsphere in dermatological treatment.

Table 1: Various research evidences of microsponges for topical drug delivery.

S. No.	Drug	Polymer	Technique	Output
1.	Curcumin	ethylcellulose and PVA	Quasi-emulsion solvent diffusion technique	The microsponges loaded in carbopol gel were evaluated for ex vivo drug deposition studies and it was found that 77.5% of the curcumin was released within 24 h. The estimated drug remained in the skin was207.61 ± 5.03 μg/cm^2 as determined by a Franz diffusion cell. The drug release profile data were found to be fitted best into the zero-order model with anomalous transport mechanism of drug release in both cases [53].
2.	Mupirocin	polyvinyl alcohol	Emulsion solvent diffusion method	Mupirocin demonstrated improved skin retention and stability in topical emulgel formulations, suggesting that the delivery mechanism has more promise for treating primary and secondary skin infections, including atopic dermatitis, eczema, and impetigo [54].
3.	Oxybenzone	poly vinyl alcohol (PVA)	Quasi-emulsion solvent diffusion method	An evaluation research found that oxybenzone had a remarkable and improved topical retention over an extended length of time. In comparison to the commercially available treatment, it also demonstrated a higher sun protection factor with less toxicity and irritation [55].
4.	Sertaconazole nitrate	Eudragit RS 100	Quasi-emulsion solvent diffusion	The secret to minimizing the negative effects of topical medication delivery systems is the controlled drug release demonstrated by microsponges-loaded gel. Formulation F4 adhered to the Higuchi model of release kinetics and demonstrated 69.38% drug release in 8 hours [56].
5.	Fluconazole	Polyvinyl Alcohol and Carbopol 937	Emulsion solvent diffusion method	Gel formulations based on microsponges demonstrated sustained effectiveness in a mouse surgical wound model infected with Candida spp. Fluconazole demonstrated improved skin retention and stability in topical formulations, suggesting that the delivery route

				has more potential for treating both primary and secondary skin infections [57].
6.	Griseofulvin (GF)	Carbopol 934	Emulsification-solvent-diffusion method	Hepatotoxicity, pharmacokinetics, and tissue distribution tests were used to evaluate the hepatoprotective and cutaneous stratum corneum retention capabilities of microsponge gel formulations in comparison to oral GF formulations. This offers a fresh viewpoint on the administration of GF dermal stratum corneum retention [58].
7.	Celecoxib	Polyvinyl Alcohol (PVA), propyl ene glycol.	Quasi-emulsion solvent diffusion method	The CXB loaded in a microsponge-based gel was found to have a regulated in vitro release profile of the medication, along with other micromeritic characteristics, entrapment efficiency, and a pleasing look [59].
8.	Miconazole nitrate	Eudragit RS100	Solvent diffusion emulsion technique	For an efficient and cost-effective treatment of diaper dermatitis, the developed miconazole nitrate gel based on microsponge technology would be a suitable alternative to conventional therapy [60].
9.	Diclofenac sodium	ethyl cellulose,	Quasi-emulsion technique	Microsponge is a rapidly developing field with a lot of promise that needs to be investigated. Because of their tiny size and effective carrier properties, microsponges make up a substantial portion [61].

Table 2: some examples of microspheres for topical drug delivery system with their application

S. No.	Active Agents	Applications
1.	Sunscreens (Oxybenzone)	Long-lasting product effectiveness, with less irritation and sensitization and better protection against sunburns and sun-related ailments even at high concentrations [62].
2.	Anti-acne (adapalene)	Reduce skin irritation and sensitivity to maintain effectiveness [63].
3.	Anti-Inflammatory (Betamethasone)	prolonged action with a decrease in dermatoses and skin allergies [64].
4.	Anti-fungal (miconazole nitrate)	Continuous release of active ingredients [65].
5.	Anti-dandruffs (Ciclopirox olamine)	less irritation, less offensive odor, and increased safety and effectiveness [66].
6.	Anti-pruritics (Hydrocortisone 1%)	enhanced and prolonged activity [67].
7.	Skin depigmenting agents (Arbutin)	enhanced effectiveness and visual appeal along with better stability against oxidation [68].
8.	Rubefacients (Methyl salicylate)	extended activity with less odor, fluid, and irritation [69].

Table 3: Recent Advances in Microsponge Drug Delivery

Sr. No.	Drug	Polymer used	Method	Application	Outcome
1	Benzoyl peroxide	Ethyl cellulose	Quasi-emulsion	Anti-acne topical	Reduced irritation, prolonged release.
2	Miconazole nitrate	Eudragit RS 100	Quasi-emulsion	Antifungal topical	Enhanced skin retention
3	Diclofenac sodium	EC + PVA	Suspension polymerization	Anti-inflammatory gel	Sustained release for 12 hours
4	Tretinoin	PMMA	Quasi-emulsion	Anti-acne cream	Improved stability, less erythema
5	Fluconazole	Eudragit RL 100	Quasi-emulsion	Antifungal	Higher entrapment

					efficiency
6	Clindamycin	Ethyl cellulose	Quasi-emulsion	Acne gel	Controlled diffusion, less dosing frequency
7	Ketoconazole	EC	Quasi-emulsion	Antifungal cream	Enhanced deposition in skin layers
8	Adapalene	Eudragit	Quasi-emulsion	Dermatology	Minimized irritation, uniform release

Critical Analysis of Reported Research on Microsponge Systems

Analysis of the reported studies indicates that the quasi-emulsion solvent diffusion method is the most widely adopted technique for microsponge preparation due to its simplicity and reproducibility. Ethyl cellulose and Eudragit polymers emerge as the most frequently used materials owing to their excellent controlled release properties. A significant proportion of research focuses on antifungal, anti-inflammatory, and anti-acne drugs for topical delivery, highlighting the dominance of dermatological applications. However, limited studies have explored the use of microsponges for delivery of biologics, peptides, and vaccines, indicating a major research gap. Additionally, most investigations remain confined to in-vitro and ex-vivo studies, with relatively fewer in-vivo and clinical evaluations reported.

Recent Patents in microsponge drug delivery

Several patents in recent years highlight the growing interest in microsponge technology for controlled drug delivery. Innovations include stimulus-responsive microsponges, biodegradable porous carriers, and microsponge-based gels for dermatological and transdermal applications. These patents focus on improving drug loading efficiency, scalability of production methods, and enhancing patient compliance through novel formulation strategies. The increasing number of patents reflect the translational potential of microsponge systems from research to commercial products.

Challenges and Limitations

Despite their promising advantages in controlled drug delivery, microsponges face several challenges and limitations that must be addressed before they can be widely adopted in pharmaceutical and cosmetic products [70]. One major hurdle is manufacturing complexity, as producing microsponges requires precise control over variables such as drug loading, porosity, and particle size. Maintaining consistency and quality during large-scale production remains difficult, with small variations potentially affecting drug release or product performance. Formulating stable and effective microsponges also involves careful selection of polymers and fine-tuning of encapsulation techniques [71]. Cost is another significant barrier; the intricate production process and need for specialized equipment drive up manufacturing and development expenses, making microsponges less accessible, especially in low-resource settings. Regulatory challenges further complicate their path to market [72]. As a relatively new technology, microsponges often fall outside existing regulatory precedents, requiring extensive safety and efficacy testing [73, 74]. The approval process involves not only validating the encapsulated drug but also demonstrating the performance of the delivery system, necessitating detailed documentation on pharmacokinetics, manufacturing, and in vivo studies. These factors collectively pose significant obstacles to the widespread use of microsponge technology [75, 76].

Research trends and growing interest in microsponge systems

A noticeable rise in scientific publications over the past decade indicates increasing research interest in microsponge-based drug delivery. Recent studies focus on biodegradable polymers, smart stimulus-responsive microsponges, and combination drug therapies. The trend reflects a shift from simple topical applications toward advanced therapeutic areas including colon targeting, vaginal delivery, and cancer therapy.

Future Prospects and Advancements

The future of microsponges looks promising, particularly with the integration of advanced technologies and the rise of personalized medicine. Nanotechnology is expected to play a key role by enabling improved targeting and precision in drug delivery, allowing microsponges to reach specific tissues or cells while minimizing side effects. It also enhances drug stability and allows for controlled, sustained release. Personalized medicine stands to benefit significantly as microsponges can be tailored to an individual's genetic profile or specific disease characteristics, optimizing drug absorption and minimizing adverse effects. Furthermore, microsponges offer potential in combination therapies by delivering multiple drugs simultaneously and fostering synergistic effects to improve outcomes, especially in complex diseases like cancer. The development of smart delivery systems, responsive to stimuli such as pH or temperature, promises localized and timely drug release, increasing treatment efficiency and safety. Beyond pharmaceuticals, microsponges are finding applications in cosmetics for controlled skincare ingredient release and show potential in immunotherapy and vaccines, where a gradual release can enhance immune responses. Lastly, with growing emphasis on environmental sustainability, the use of biodegradable materials in

microsponge design is gaining traction, ensuring safety for both the body and the planet.

Commercial products based on microsponge technology

Microsponge technology has been translated into several commercial dermatological and cosmetic formulations. Marketed products containing benzoyl peroxide, tretinoin, and sunscreen agents utilize microsponge systems to reduce irritation, enhance stability, and prolong therapeutic action. This successful commercialization highlights the practical applicability and industrial acceptance of microsponge drug delivery systems.

Conclusion

Microsponges have established themselves as a robust platform for controlled, sustained, and site-specific drug delivery owing to their porous architecture, high drug-loading capacity, and formulation versatility. Among the available fabrication routes, quasi-emulsion solvent diffusion is most widely adopted for its simplicity and reproducibility, while polymers such as ethyl cellulose and Eudragit predominate due to their reliable release-modulating properties. Contemporary research is largely centered on dermatological and topical therapies, where microsponges demonstrably reduce irritation, enhance stability, and prolong therapeutic action. At the same time, clear opportunities remain in expanding their use toward oral, transdermal, and advanced applications including delivery of biologics, peptides, and vaccines. Despite challenges related to scale-up, solvent handling, and regulatory standardization, ongoing advances in biodegradable polymers, stimulus-responsive matrices, and process optimization are steadily addressing these limitations. The growing body of recent research, patents, and commercial formulations underscores the translational potential of this technology. With continued refinement, microsponge systems are poised to become an integral component of modern pharmaceutical and cosmetic formulations, offering safer, more effective, and patient-friendly therapeutic solutions across diverse clinical and consumer applications.

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