Microsponge Technology in The Era of Nanomedicine: Associating Conventional and Advanced Drug Delivery Systems

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Abstract*—Microsponge technology has arose as a erudite and multipurpose drug delivery podium accomplished of talking frequent boundaries related with conventional pharmaceutical dosage forms. Characterized by highly porous, cross-linked polymeric microspheres, microsponges facilitate controlled, site-specific, and sustained release of API while ornamental medicament stability, plummeting systemic toxicity, and refining patient compliance. Their exclusive absorbent manner allows well-organized encapsulation of miscellaneous medicinal agents, counting synthetic drugs, biologics, and phytopharmaceuticals, thus expansion their pertinence crossways manifold beneficial areas. Current review expansively reconnoitres the central ideologies, fabrication methodologies, physicochemical features, and modern progressions in microsponge-based drug delivery systems. Specific importance is positioned on traditional fabrication methods, counting quasi-emulsion solvent diffusion, suspension polymerization, and solvent evaporation techniques, alongside emerging technologies such as microfluidics, spray drying, supercritical fluid processing, electrohydrodynamic atomization, and three-dimensional printing. Additionally, the review unsympathetically scrutinizes the developing incorporation of microsponge technology with nanomedicine, importance the expansion of nano-embedded microsponges, hybrid nano–microsponge systems, stimuli-responsive carriers, and multifunctional nanocomposites intended to improve healing exactness and targeted drug delivery. Advanced microsponge systems including pH-responsive, thermo-responsive, enzyme-responsive, magnetic, floating, bioadhesive, colon-targeted, pulmonary, ocular, antimicrobial, and anticancer microsponges are deliberated with respect to their mechanistic attributes, therapeutic applications, and translational potential. Furthermore, contemporary innovations linking AI-assisted formulation optimization, Quality-by-Design strategies, and personalized medicine approaches are evaluated. Together, microsponge technology represents a critical bridge between unadventurous pharmaceutical systems and advanced nanotherapeutic stages, contribution substantial potential for the development of next-generation, patient-centric, and clinically translatable drug delivery systems.

***Index Terms*—Microsponge, Drug delivery, QbD, Nanomedicine, Microsphere**

I. INTRODUCTION

Drug delivery systems have experienced extraordinary development over the past few eras, getting systematic conversion from traditional medicinal system toward sophisticated carrier-based platforms accomplished of refining therapeutic efficacy, patient compliance, and targeted drug action (1). Outmoded dosage forms such as tablets, capsules, and topical preparations often agonize from numerous boundaries, counting poor bioavailability, quick medicament dilapidation, recurrent dosing supplies, systemic adverse event, and non-specific distribution. These encounters have stimulated all-embracing investigations into progressive drug delivery technologies that can enhance drug release kinetics and improve therapeutic outcomes (2).

Amongst the innumerable carrier-based systems industrialized, microsponge technology has arose as a multipurpose and ground-breaking podium for controlled and site-specific drug delivery. They are highly porous, polymeric microspheres branded by consistent cavities accomplished of deceiving extensive variety of API. Their exclusive porous manner allows controlled release of drugs over protracted epochs while protecting sensitive molecules from environmental

degradation (3). Additionally, microsponges hold outstanding constancy, high drug-loading capacity, abridged irritation potential, and improved patient acceptability, making them particularly attractive for topical, oral, and targeted therapeutic applications (4). Over the period of time, beginning of nanomedicine has transfigured contemporary medicinal sciences by presenting nanoparticles, liposomes, dendrimers, polymeric micelles, nanosponges, and lipid-based nanocarriers. These progressive novel medicine approach determine the greater targeting competences, improved cellular uptake, better-quality bioavailability, and the aptitude to overwhelmed pharmacological limitations. Nevertheless, encounters together with complex manufacturing processes, stability issues, high production costs, and potential toxicity continue to limit their widespread clinical translation (5).

Microsponge technology signifies an important connection between conventional drug delivery systems and advanced nanomedicine. Current advancement has absorbed on participating microsponge platforms with nanotechnology to form hybrid delivery systems that syndicate the compensations of both tactics. Stimuli-responsive microsponges, nano-embedded microsponges, multifunctional polymeric carriers, and targeted delivery systems have expanded the therapeutic potential of microsponges beyond traditional applications. These novelties have simplified the delivery of antimicrobial, anticancer, anti-inflammatory, and herbal therapeutics with enhanced precision and controlled release characteristics (6).

The present review highlights the fundamental principles of microsponge technology, recent advancements in formulation strategies, and pharmacological applications, while emphasizing its evolving role in the era of nanomedicine. Specific consideration is given to the addition of microsponge systems with modern nanotechnological approaches, exemplifying their latent as next-generation medication delivery stages accomplished of connecting unadventurous medicinal preparations & progressive battered rehabilitations.

II. RUDIMENTS OF MICROSPONGE TECHNOLOGY

Structure and Characteristics

They are highly cross-linked porous polymeric microspheres characteristically fluctuating from 5 to 300 μm in diameter. These are made up of 3D system of consistent pores accomplished of deceiving API within their interior assembly. The porous planning delivers a large surface area, permitting well-organized drug loading and controlled release. Microsponge particles are usually spherical, free-flowing, non-collapsible, and chemically stable over a wide pH and temperature range. Frequently active polymers comprise ethyl cellulose, Eudragit®, polyvinyl alcohol, polymethacrylates, and biodegradable polymers. Due to their porous nature, microsponges can recall vigorous complexes while diminishing squalor instigated by ecological influences such as light, oxygen, moisture, and heat (7).

Mechanism of Drug Entrapment

During the manufacturing operations of microsponges, while instigate the API into the plymer matrix, drug entrapment can be occurred. In the frequently active quasi-emulsion solvent diffusion system, the drug and polymer are liquified in an organic solvent establishing the internal phase and then discrete into an aqueous external phase covering stabilizers (8). As the solvent diffuses and vanishes, polymer precipitation happens, subsequent in the development of porous microspheres with the drug entrapped within the interconnected cavities. Drug molecules may be physically encapsulated, adsorbed onto pore surfaces, or uniformly dispersed throughout the polymeric network (9). The extent of entrapment is influenced by factors such as drug-polymer compatibility, polymer concentration, solvent selection, stirring speed, and preparation conditions (8).

Physiology of Drug Proclamation from Microsponges

Drug release from microsponges is administered by diffusion through the porous matrix and is prejudiced by both formulation variables and external environmental circumstances. Proclamation may occur through diffusion of melted drug molecules from interconnected pores, gradual desorption from pore surfaces, polymer erosion, or swelling of the polymer matrix. External initiations such as temperature, pH, pressure, moisture, and mechanical rubbing can further modulate drug release rates. In topical formulations, drug release often occurs when the formulation is applied to the skin and exposed to physiological temperature and moisture

conditions. Controlled release behaviour assistances uphold beneficial medicine attentions, ended protracted aeras while diminishing peak adverse events (10).

Advantages and Limitations

Several advantages are driven by Microsponge technology over conventional drug delivery systems. They involve controlled and sustained drug release, improved stability of active ingredients, high drug-loading capacity, abridged irritation, better patient acquiescence, and defence of medications from environmental dilapidation. The porous structure simplifies well-organized delivery of both hydrophilic and lipophilic complexes while plummeting systemic absorption and toxicity. Additionally, microsponges can be combined into numerous dosage forms counting gels, creams, tablets, capsules, and transdermal systems (11).

Apart from this, certain limitations remain are there. The technology is usually more appropriate for drugs with reasonable molecular weight and incomplete aqueous solubility (12). Invention complexity, reproducibility apprehensions, polymer selection restraints, and scale-up encounters may affect industrial manufacture. Moreover, achieving uniform particle size distribution and high encapsulation efficiency can be problematic for certain active compounds. However, continuous progressions in polymer engineering and nanotechnology are addressing these challenges and expanding the therapeutic potential of nanomedicine (13).

III. FORMULATION APPROACHES FOR MICROSPONGES

Major parameter for the successful development of microsponge drug delivery systems depends largely on the assortment of suitable fabrication technique. Numerous formulation methodology has been assigned for the stimulation of the nanomedicine such as microsponges with anticipated particle size, porosity, drug-loading capacity, and release appearances. Preparation tactic is prejudiced by the physicochemical possessions of the drug, polymer type, intended route of administration, and desired therapeutic outcome. Current methodology include quasi-emulsion solvent diffusion, suspension polymerization, and solvent evaporation techniques are the most extensively hired. Current intensive development of the technology has additional presented advanced fabrication approaches capable of producing highly erudite microsponge systems with enhanced performance characteristics.

Table 1. Comparison of Microsponge Fabrication Techniques and Key Parameters

S. No.	Fabrication Technique	Principle	Material Utilized	Critical Process Parameters	Advantages	Limitations	Typical Applications	Ref.
1	Quasi-Emulsion Solvent Diffusion	Diffusion of organic solvent into aqueous phase followed by polymer precipitation and pore formation	Eudragit RS100, Ethyl cellulose, ethanol, acetone, PVA, dichloromethane	Stirring speed, polymer concentration, solvent type, PVA concentration, internal/external phase ratio, temperature	Simple, reproducible, suitable for thermolabile drugs, high entrapment efficiency	Residual solvent concerns, particle size variation if parameters are not optimized	Topical gels, creams, oral controlled-release formulations	(14)
2	Suspension Polymerization	Polymerization of monomers suspended in aqueous medium forming highly cross-linked	Monomers, cross-linkers, initiators, drug, aqueous dispersion medium	Monomer concentration, cross-linking density, stirring speed, polymerization temperature,	Excellent structural integrity, high porosity, good mechanical strength	Use of residual monomers, complex process, higher production cost	Controlled drug delivery, long-term release systems	(15)

		porous particles		initiator concentration				
3	Solvent Evaporation Technique	Evaporation of volatile solvent leading to polymer precipitation around drug molecules	Drug, polymer, volatile solvent, stabilizers	Solvent evaporation rate, stirring speed, polymer concentration, surfactant concentration, temperature	Easy operation, scalable, suitable for poorly water-soluble drugs	Complete solvent removal required, possible drug leakage	Oral, topical and transdermal drug delivery	(15)
4	Ultrasound-Assisted Fabrication	Acoustic cavitation generates uniform emulsion droplets and porous particles	Drug, polymer, solvent system	Ultrasound frequency, sonication time, amplitude, temperature	Uniform particle size, improved porosity, enhanced encapsulation efficiency	Equipment cost, possible degradation of sensitive drugs	Advanced controlled-release systems	(16)
5	Microfluidic Fabrication	Controlled fluid flow at microscale produces monodisperse microsponge particles	Drug, polymer solutions, microfluidic chips	Flow rate, channel geometry, pressure, polymer concentration	Precise particle size control, high reproducibility, uniform morphology	Expensive setup, low production throughput	Personalized medicine, targeted drug delivery	(17)
6	Spray Drying	Atomization of drug-polymer solution followed by rapid solvent evaporation	Drug, polymer, volatile solvent	Inlet temperature, feed rate, atomization pressure, outlet temperature	Rapid, scalable, continuous production	Heat-sensitive drugs may degrade, lower porosity in some cases	Industrial-scale microsponge production	(18)
7	Supercritical Fluid Technology	Use of supercritical fluids for solvent extraction and pore generation	Drug, polymer, supercritical CO_2	Pressure, temperature, flow rate, polymer concentration	Solvent-free, environmentally friendly, highly porous particles	High equipment cost, complex operation	High-value pharmaceutical products	(19)
8	Electrohydrodynamic Atomization	Electric field generates micro-droplets which solidify into porous particles	Drug, polymer solution, conductive solvent	Voltage, flow rate, needle-to-collector distance, solution viscosity	Narrow particle size distribution, controlled morphology	Limited scalability, specialized equipment required	Targeted and controlled drug delivery	(20)
9	3D Printing-Based Fabrication	Layer-by-layer fabrication	Drug-loaded polymer inks	Printing speed, nozzle	Personalized dosage forms,	High production cost,	Personalized medicine and	(21)

		of customized porous microsponge systems		diameter, layer thickness, printing temperature	complex architectures	formulation limitations	implantable systems	
10	Nano-Embedded Microsponge Fabrication	Incorporation of nanoparticles within microsponge matrix for dual delivery	Drug, polymer, nanoparticles	Nanoparticle concentration, polymer ratio, particle size, stirring conditions	Dual drug delivery, enhanced targeting, improved bioavailability	Complex formulation process, stability concerns	Nanomedicine, anticancer and targeted therapy	(22)

IV. BRIDGING MICROSPONGE TECHNOLOGY AND NANOMEDICINE

- Microsponge technology inhabits a sole location amid traditional drug system and current nanomedicine. Microsponges deliver outstanding regulator over drug announcement through their porous polymeric manner, nanocarriers offer greater targeting and cellular penetration competences. Participating these skills has led to the expansion of hybrid systems that syndicate the stability and high loading capacity of microsponges with the targeting potential of nanomedicine (23).
- Microsponges are micron-sized porous assemblies chiefly intended for controlled drug release, whereas nanocarriers function at the nanoscale and are often utilized for targeted and intracellular delivery. Microsponges possess greater structural stability and drug-loading capacity, while nanocarriers exhibit enhanced tissue penetration and cellular uptake.
- Together arrangement's goal to recover drug stability, bioavailability, and therapeutic efficacy. Though, they differ meaningfully in particle size, preparation methods, release mechanisms, and biological interactions. The combination of these complementary properties forms the basis for next-generation hybrid delivery systems.
- Hybrid delivery systems join nanoscale carriers within porous microsponge matrices to accomplish dual-controlled release and targeted delivery. These systems offer better-quality therapeutic performance and reduced toxicity.
- Nano-embedded microsponges consist of nanoparticles encapsulated within microsponge pores. Such systems provide multi-stage release kinetics, enhanced protection of active agents, and improved targeting capabilities.
- Microsponge-based nanocomposites integrate nanomaterials with polymeric microsponges to generate multifunctional carriers exhibiting superior mechanical, physicochemical, and biological properties.
- Current advancement has altered outdated microsponges into smart and multifunctional delivery platforms.

Table 2. Type of Microsponge with Stimulus, applications and illustrations followed by limitations

S. No.	Type of Microsponge	Description	Stimulus	Major Applications	Representative Example	Limitations	Ref.
1	Conventional Microsponges	Porous polymeric microspheres providing sustained drug release.	Diffusion-controlled release	Topical and oral drug delivery	Benzoyl peroxide microsponge gel	Limited loading of hydrophilic drugs; burst release may occur.	(24)
2	Bioadhesive Microsponges	Formulated with mucoadhesive polymers to prolong residence time.	Adhesion to mucosal tissues	Buccal, ocular, nasal delivery	Chitosan-based metronidazole microsponges	Possible mucosal irritation and polymer-related discomfort.	(25)

3	Floating Microsponges	Low-density porous systems that remain buoyant in gastric fluid.	Gastric flotation	Gastroretentive delivery	Famotidine floating microsponges	Unsuitable for drugs unstable in gastric environment; depends on gastric emptying rate.	(26)
4	Colon-Targeted Microsponges	Drug release occurs specifically in the colon.	pH-sensitive polymer degradation	Ulcerative colitis, colon cancer	Mesalamine microsponges	Variable gastrointestinal pH may affect targeting efficiency.	(27)
5	Magnetic Microsponges	Incorporate magnetic nanoparticles for targeted delivery.	External magnetic field	Site-specific cancer therapy	Doxorubicin-loaded magnetic microsponges	Requires external magnetic device; potential nanoparticle toxicity.	(28), (29), (30)
6	Nano-Embedded Microsponges	Nanoparticles incorporated within microsponge matrix.	Nano–micro hybrid release	Targeted and controlled delivery	Curcumin nanoparticle-loaded microsponges	Complex manufacturing and stability challenges.	(31)
7	Stimuli-Responsive Microsponges	Intelligent systems responding to environmental triggers.	External/Internal stimuli	Precision medicine	Smart insulin microsponges	Expensive fabrication and difficult scale-up.	(32)
8	pH-Responsive Microsponges	Drug release triggered by pH variation.	pH-dependent swelling or degradation	Colon and gastric delivery	Eudragit-based 5-Fluorouracil microsponges	Drug release may vary due to patient-to-patient pH differences.	(33)
9	Thermo-Responsive Microsponges	Release drugs when temperature changes occur.	Temperature-sensitive polymers	Hyperthermia-assisted therapy	PNIPAM-based drug-loaded microsponges	Temperature fluctuations may cause premature release.	(34)
10	Light-Responsive Microsponges	Drug release activated by UV or near-infrared light.	Photochemical activation	Photodynamic therapy	Photosensitizer-loaded microsponges	Limited tissue penetration of light; specialized equipment required.	(35)
11	Enzyme-Responsive Microsponges	Drug release occurs in presence of disease-specific enzymes.	Enzymatic degradation	Cancer and inflammatory disorders	Matrix metalloproteinase-responsive microsponges	Enzyme levels vary among patients and disease stages.	(36)
12	Redox-Responsive Microsponges	Triggered by oxidative/reducti	Redox-sensitive bond cleavage	Tumor-targeted drug delivery	Disulfide-linked doxorubicin microsponges	Limited applicability outside	(37)

		ve intracellular environment.				redox-altered tissues.	
13	Herbal Microsponges	Encapsulation of herbal extracts for improved stability and release.	Diffusion-controlled release	Herbal therapeutics	Curcumin, Aloe vera, Clitoria ternatea microsponges	Variability in herbal extract composition affects reproducibility.	(38)
14	Protein/Peptide-Loaded Microsponges	Designed for delivery of proteins and peptides.	Controlled diffusion and matrix erosion	Biologics delivery	Insulin-loaded microsponges	Protein instability and denaturation during processing.	(39), (40)
15	Hybrid Nano-Microsponges	Combination of nanocarriers and microsponges in a single platform.	Multi-mechanistic release	Personalized medicine	Liposome-loaded microsponge system	Complex formulation and higher production cost.	(41)
16	Ocular Microsponges	Designed for prolonged retention in ocular tissues.	Controlled release	Glaucoma and eye infections	Timolol maleate microsponges	May cause blurred vision or ocular irritation.	(42)
17	Pulmonary Microsponges	Inhalable porous particles for lung targeting.	Sustained pulmonary release	Asthma and COPD	Salbutamol microsponge dry powder	Requires optimized aerodynamic properties for lung deposition.	(41)
18	Dermal/Topical Microsponges	Most widely used microsponge systems for skin application.	Diffusion through pores	Acne, fungal infections, psoriasis	Benzoyl peroxide microsponge gel (Retin-A Micro®)	Limited penetration through deeper skin layers.	(14)
19	Antimicrobial Microsponges	Loaded with antimicrobial agents for prolonged local action.	Sustained release	Skin and wound infections	Mupirocin microsponge gel	Risk of microbial resistance with prolonged exposure.	
20	Anticancer Microsponges	Designed for localized and sustained chemotherapy.	Controlled and targeted release	Cancer treatment	Paclitaxel-loaded microsponges	Difficult tumor penetration and complex regulatory approval process.	(42)

V. CONCLUSION

Microsponge technology has progressed from a humble controlled-release podium into a erudite multifunctional drug delivery system with widespread beneficial possible. Its capability to deliver sustained release, high drug-loading capacity, improved stability, and better-quality patient compliance has recognized microsponges as valuable pharmaceutical carriers. The conjunction of microsponge technology with nanomedicine has led to the appearance of hybrid systems accomplished of combination the compensations of both micro- and nanoscale delivery podiums. Sustained progressions in polymer science, nanotechnology, artificial intelligence, and precision

medicine are predictable to additional enlarge the clinical usefulness of microsponges. Accordingly, microsponge-based hybrid systems are probable to production a essential character in the next generation of targeted and personalized drug delivery policies.

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