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Review Article

NANOSPONGES: A Novel Approach in Acne Therapy

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ABSTRACT

Acne vulgaris is a widespread inflammatory condition involving the pilosebaceous unit and is commonly seen in both teenagers and adults. Its development is influenced by several interconnected factors, including increased sebum secretion, abnormal follicular keratinization, growth of Cutibacterium acne, and associated inflammation. Conventional treatment options such as retinoids, benzoyl peroxide, antibiotics, and systemic therapies are commonly prescribed; however, their clinical outcomes are often restricted due to limited skin penetration, irritation, instability of formulations, and the rising issue of antibiotic resistance. To address these limitations, nanotechnology-based drug delivery systems have gained increasing interest. Nanosponges, in particular, have shown promise as advanced carriers owing to their nanoscale, porous, and three-dimensional structure. These systems can incorporate both hydrophilic and lipophilic drugs, thereby improving solubility, stability, and overall drug performance. They also support prolonged and controlled drug release, enhance retention within the skin, and enable more localized delivery to the pilosebaceous unit. This review summarizes the underlying mechanisms of acne, current therapeutic challenges, and the potential role of nanosponges in improving treatment and future perspective.

INTRODUCTION

Acne is a skin condition that occurs due to changes in the sebaceous (oil) glands. The most common type is known as acne vulgaris, which simply means “common acne.” The redness seen in acne is mainly due to inflammation of the skin. When excess oil produced by the glands mixes with dead skin cells, it can block the hair follicles. This blockage allows oil to accumulate beneath the skin, creating a favourable environment for bacteria to grow rapidly. As a result, the affected area becomes swollen, red, and sometimes painful. Acne most commonly appears on the face, chest,

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back, and upper arms. Acne is frequently observed during puberty, a stage when the body undergoes hormonal changes from childhood to adulthood. These hormonal fluctuations increase oil production, making adolescents more prone to acne. However, the condition often improves as a person grows older. The word "acne" is derived from the Greek term "acme," meaning the "prime of life," which reflects its high occurrence during adolescence. Although acne is generally considered a mild and self-limiting condition, it can sometimes lead to serious psychological effects and permanent scarring. Acne is a complex disorder that can present in different forms and may occur at any stage of life, but it is most seen between the ages of 12 and 24, affecting nearly 85% of individuals. Additionally, many adults, particularly those between 20 and 30 years of age, may continue to experience acne. Acne vulgaris is one of the most widespread skin disorders affecting the pilosebaceous unit, and almost everyone experiences it at least once in their lifetime. While it is most common during the teenage years, it can also persist into adulthood in both men and women. [1] Acne vulgaris is a long-term inflammatory condition of the pilosebaceous unit that commonly affects teenagers and young adults. It appears in different forms, including non-inflammatory lesions like comedones (blackheads and whiteheads) as well as inflammatory lesions such as papules, pustules, and nodules. In some cases, it can result in permanent scarring and emotional or psychological discomfort. The development of acne is linked to several contributing factors, including excessive production of sebum, abnormal shedding of skin cells leading to blockage of hair follicles, growth of *Cuti bacterium acnes*, and the resulting inflammatory response in the skin. [2,3] Conventional acne therapies, including topical retinoids, antibiotics, and benzoyl peroxide, are widely used but are often associated with limitations such as poor skin penetration, local irritation, instability, and the development of antibiotic resistance. These challenges necessitate the development of advanced drug delivery systems to enhance therapeutic efficacy and patient compliance [4] Nanotechnology-based carriers have emerged as promising tools in dermatological drug delivery due to their ability to improve drug solubility, stability, and targeted delivery. Among these, nanosponges have gained considerable attention as a novel drug delivery system [5] Nanosponges are nanosized, highly porous, three-dimensional polymeric structures, commonly based on cross-linked cyclodextrins, capable of encapsulating both hydrophilic and lipophilic drugs. Their unique porous architecture enables high drug loading, protection of active ingredients from degradation, and controlled release of drugs over an extended period. Additionally, nanosponges enhance drug retention in the skin, reduce irritation, and improve therapeutic outcomes, making them particularly suitable for topical applications such as acne therapy [6,7] Thus, nanosponges represent a promising and innovative approach for topical drug delivery in acne management.

CAUSATIVE FACTORS AND PATHOGENESIS OF ACNE VULGARIS [8,11]

Several factors are known to contribute to the development of acne vulgaris. As mentioned earlier, this chronic skin condition is mainly associated with increased sebum production, hormonal influences—particularly androgens—abnormal keratinization within the follicular infundibulum, proliferation of bacteria, and the resulting inflammatory response.

a) Increase in Sebum production: Excess sebum production within the hair follicles is one of the major factors responsible for the development of

acne. As reported hormonal influences particularly androgens like testosterone and insulin-like growth factor (IGF-1) stimulate the synthesis and release of sebum. There is a strong association between elevated sebum levels and the severity as well as frequency of acne lesions. Therefore, increased sebum production is considered a key factor in the pathogenesis of acne vulgaris.

b) Hyperkeratinization abnormalities of the pilosebaceous follicles: Under normal conditions, healthy hair follicles continuously shed individual keratinocytes into the lumen, where they are eventually removed. In individuals with acne, however, keratinocytes undergo excessive proliferation and are not shed properly. This results in the buildup of irregularly desquamated corneocytes within the pilosebaceous follicles, along with lipids and filamentous material, ultimately contributing to follicular blockage.

c) Hyper proliferation of Propionibacterium acnes (P. acnes): *Cuti bacterium acnes* (formerly known as *Propionibacterium acnes*) plays an important role in the development of inflammatory acne. It is an anaerobic, lipophilic, gram-positive bacterium that preferentially colonizes sebaceous follicles, as these sites provide a lipid-rich and low-oxygen environment suitable for its growth. This microorganism produces lipase enzymes that break down sebum triglycerides into glycerol and free fatty acids. These by-products contribute to the formation of comedones and promote inflammatory responses in the skin.

d) Inflammation acne: Following the proliferation of *Cuti bacterium acnes*, the immune system recognizes the bacteria and initiates an inflammatory response. *C. acnes* have a strong ability to trigger inflammation by attracting immune cells such as neutrophils, lymphocytes, and macrophages. This immune activity can damage the follicular wall, leading to its rupture and the release of bacteria, fatty acids, and lipids into the dermis. These events contribute to the formation of inflammatory lesions, including papules, pustules, nodules, and cysts. In contrast, non-inflammatory lesions are typically smaller and contain less pus. Furthermore, neutrophils produce reactive oxygen species (ROS), which can damage the follicular epithelium and intensify the inflammatory process. As a result, the contents of the follicle are expelled into the surrounding dermal tissue, leading to the development of various inflammatory acne lesions.

e) DNA Methylation: Environmental stress can influence gene expression through epigenetic modifications, which act as a link between genetic makeup and environmental factors. One of the most widely studied epigenetic mechanisms is DNA methylation. In recent years, it has gained considerable attention in dermatology due to its role in regulating the underlying mechanisms of various skin conditions, including inflammatory, autoimmune, and cancer-related disorders.

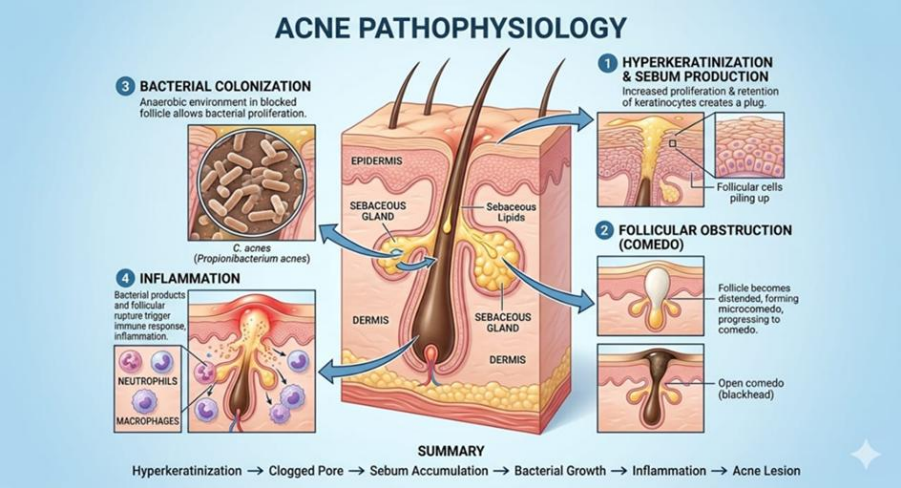

Fig.1. Acne Pathophysiology

Conventional Therapies For Acne: [9]

1. Topical Therapy

Topical treatments are generally considered the first choice for managing mild to moderate acne.

Topical retinoids (e.g., tretinoin, adapalene): These agents help regulate the shedding of skin cells, prevent the formation of comedones, and possess anti-inflammatory properties. They are widely regarded as the foundation of acne treatment.

Benzoyl peroxide (BPO): BPO acts as a strong antimicrobial agent against *Cutibacterium acnes*. It is often used in combination with antibiotics to reduce the risk of developing bacterial resistance.

Topical antibiotics (e.g., clindamycin, erythromycin):
These medications work by decreasing bacterial growth and inflammation. However, they are typically recommended in combination with BPO to limit antibiotic resistance.

Azelaic acid:
Azelaic acid exhibits comedolytic, antibacterial, and anti-inflammatory effects. It is particularly useful for individuals with sensitive skin and those experiencing post-inflammatory hyperpigmentation

2.Systemic Therapy

Systemic treatments are usually reserved for moderate to severe acne or when topical therapies are not effective.

Oral antibiotics (e.g., doxycycline, minocycline):
These drugs help reduce *C. acnes* levels and inflammation. However, prolonged use is generally avoided due to concerns about antibiotic resistance.

Hormonal therapy (e.g., oral contraceptives, spironolactone):
These treatments are effective in female patients by decreasing androgen-induced sebum production.

Oral isotretinoin:
Isotretinoin is considered one of the most effective options for severe or treatment-resistant acne, as it targets multiple pathogenic factors. It works by reducing sebum production, normalizing

keratinization, decreasing bacterial colonization, and providing anti-inflammatory effects. However, its use is restricted due to serious side effects, including teratogenicity, and requires careful monitoring.

Combination Therapy

Combination treatments, such as retinoid with BPO or antibiotics with BPO, are often more effective than single-drug therapy. This approach targets multiple underlying mechanisms of acne, helps reduce the risk of resistance, and leads to better clinical outcomes.

Limitations of Conventional Therapy

Although conventional treatments are effective, they have several limitations. These include the growing issue of antibiotic resistance, skin irritation and dryness (commonly seen with retinoids and BPO), recurrence of acne after stopping treatment, and systemic side effects—especially with isotretinoin. In addition, long treatment durations can lead to poor patient adherence.

Nanosponges: [10,12]

Nanosponges are nanosized, porous, mesh-like structures capable of entrapping a wide variety of substances, which can then be incorporated into different dosage forms. They are typically spherical and exhibit a colloidal nature, with a highly porous architecture that enhances the solubility of poorly water-soluble drugs through both inclusion and non-inclusion mechanisms. In recent years, nanosponges have gained considerable attention as effective drug delivery carriers due to their ability to improve drug solubility, increase bioavailability, and provide controlled as well as prolonged drug release. Their unique structure consists of hydrophobic inner cavities and hydrophilic outer surfaces, allowing them to accommodate both hydrophilic and hydrophobic drugs. Structurally, they form a three-dimensional network made of crosslinked polymers, such as polyesters, where small crosslinking agents connect polymer chains to create a stable and porous framework capable of encapsulating drug molecules within its core. Nanosponges are considered encapsulating-type nanoparticles, as they enclose drug molecules within their internal cavities. Unlike vesicular systems, they possess an open porous structure without a continuous outer membrane, allowing the drug to remain in dynamic equilibrium with the surrounding vehicle. Upon application, such as on the skin, this equilibrium is disturbed due to evaporation or absorption of the vehicle, leading to a gradual release of the drug from the nanosponge into the vehicle and then into the skin. This process continues until a new equilibrium is achieved. Even after the vehicle is partially removed, nanosponge particles remain adhered to the surface of the skin, particularly in the stratum corneum, and continue to release the active substance over an extended period. This sustained release behavior enhances therapeutic effectiveness and reduces the need for frequent dosing.

Nanosponge Design And Materials [13,14]

Nanosponges have a unique and interesting structure. They are tiny, spherical particles with a porous nature, which allows them to trap different types of drug molecules inside their internal cavities. Because of their very small size and large surface area, they can carry a significant amount of drug and help in controlling how the drug is released over time. One of the most important features of nanosponges is their network of interconnected pores. These pores can be adjusted in size and density depending on the requirement,

which makes it possible to design nanosponges for specific drug release patterns. This porous structure not only helps in holding the drug but also protects it from environmental factors such as light, oxygen, and moisture, thereby improving the stability of the drug Nanosponges are generally prepared using biocompatible materials like cyclodextrins and different polymers. Cyclodextrins are cyclic molecules that have a water-repelling (hydrophobic) inner cavity and a water-attracting (hydrophilic) outer surface. This special structure allows them to carry poorly water-soluble drugs inside while still being compatible with aqueous environments. Because of this property, cyclodextrin-based nanosponges are especially useful in topical drug delivery, as they improve drug solubility and enhance skin penetration. Apart from cyclodextrins, polymers such as polyester, polyvinyl alcohol, and polycaprolactone are also commonly used. These materials can be modified to achieve desired properties like biodegradability, strength, and porosity depending on the intended use. Different preparation methods, including emulsion solvent evaporation, melt sonication, and cross-linking, are used to produce nanosponges. Each method affects important characteristics such as particle size, pore structure, and drug-loading capacity.

Chemicals In The Preparation Of Nanosponge[15-17]

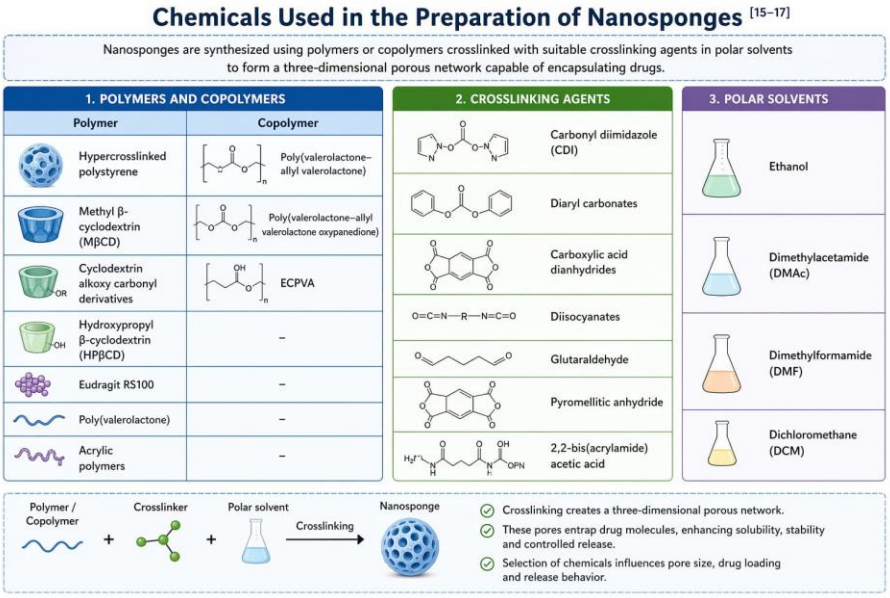

Fig.2. Chemicals Used in the Preparation Of Nanosponge

Mechanism Of Drug Release From Nanosponges[18,19]

Nanosponges possess a porous, open structure without a continuous outer membrane, allowing active pharmaceutical ingredients to be incorporated within their cavities in an encapsulated form. Once loaded, the active substance can diffuse freely from the nanosponge into the surrounding vehicle until a state of equilibrium is reached. Upon topical application, the vehicle becomes unsaturated due to absorption or evaporation, which disrupts this equilibrium. This imbalance drives the gradual release of the active compound from the nanosponges into the vehicle and subsequently into the epidermis. Moreover, even after the nanosponge particles remain adhered to the surface layer of the skin

(stratum corneum), they continue to provide sustained release of the active ingredient over an extended period.

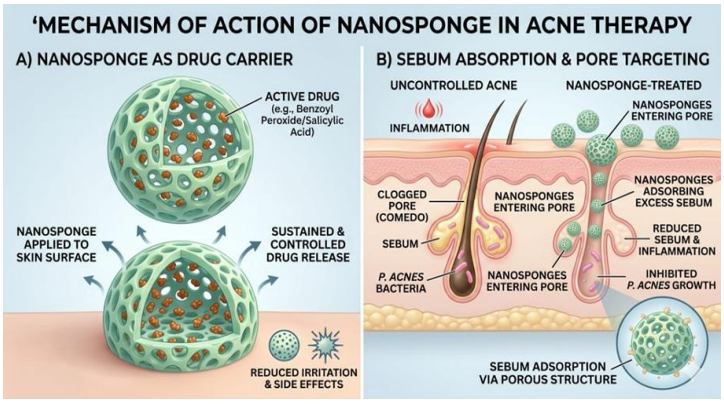

Fig.3. Mechanism Of Action in Acne Therapy

Mechanism Of Nanosponges In Acne Therapy

Nanosponges are porous, three-dimensional polymeric carriers, most based on cyclodextrins, that can encapsulate both hydrophilic and lipophilic drugs within their nano-sized cavities. By forming these inclusion complexes, they act as tiny reservoirs that protect the drug from degradation and improve its overall stability [20,21] Because of their small size and unique structure, nanosponges can easily localize within the pilosebaceous unit, which is the primary site of acne formation. This allows for more targeted delivery of therapeutic agents directly to the affected area, helping to increase drug concentration at the site of action while minimizing systemic exposure [22,23] Once delivered, the drug is released slowly and in a controlled manner from the nanosponge matrix. This sustained release helps maintain a consistent therapeutic level over a longer period, reducing the need for frequent application and avoiding the sudden burst release commonly seen with conventional topical formulations [24] In addition, nanosponges improve the solubility and penetration of poorly water-soluble drugs. Their amphiphilic nature enables better interaction with the skin barrier, allowing the drug to pass through the stratum corneum and reach deeper layers more effectively [25] When loaded with antimicrobial agents , nanosponges provide prolonged antibacterial activity against Cuti bacterium acnes. This sustained action helps in reducing bacterial growth and may also lower the chances of developing antibiotic resistance compared to traditional treatments . Furthermore, the controlled release of drugs helps minimize skin irritation and inflammation, which are common side effects of many topical acne therapies. As a result, symptoms such as redness, swelling, and lesion severity are reduced, improving overall skin tolerability. Overall, nanosponges work through a combination of targeted delivery, controlled drug release, enhanced penetration, and reduced side effects, making them a promising and effective approach for the management of acne vulgaris.[26]

METHODS OF NANOSPONGES PREPARATION:

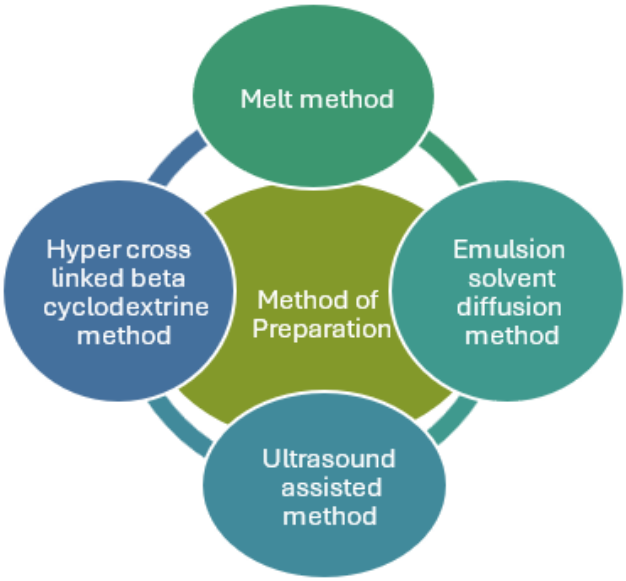

Fig.4. Methods Of Preparation

1.Emulsion Solvent Diffusion Method [27]:

Nanosponges can be formulated by using different ratios of ethyl cellulose (EC) and polyvinyl alcohol (PVA) via a simple emulsion solvent diffusion technique. In this method, the drug and ethyl cellulose are first dissolved in 20 mL of dichloromethane to form the organic (dispersed) phase. This solution is then gradually added into an aqueous phase containing a specific amount of PVA under continuous stirring. The system is stirred at around 1000 rpm for about 2 hours, allowing the formation of nanosponge particles. These formed nanosponges are then separated by filtration and dried in an oven at 40°C for 24 hours. After drying, they are stored in a vacuum desiccator to remove any remaining traces of solvent and to maintain their stability.

2.Nanosponges prepared from Hyper Cross Linked β Cyclodextrins [28-31]:

Nanosponges are a recently developed class of hyper–cross-linked cyclodextrin-based nanostructures that form a three-dimensional porous network. These structures are typically spherical and comparable in size to proteins, with numerous internal cavities and channels that enable drug encapsulation. Nanosponges are synthesized by reacting cyclodextrins with various cross-linking agents such as diisocyanates, diaryl carbonates, dimethyl carbonate, diphenyl carbonate, carbonyl di-imidazole, carboxylic acid dianhydrides, and 2,2-bis(acrylamido) acetic acid. The physicochemical properties of nanosponges, including surface charge, porosity, and pore size, can be tailored by adjusting the degree of cross-linking, which in turn influences drug loading and release behaviour. Notably, a lower degree of cross-linking generally results in faster drug release β-cyclodextrin-based nanosponges can be prepared using a solvent-based method. In a typical procedure, 100 mL of dimethylformamide (DMF) is taken in a round-bottom flask, and 17.42 g of anhydrous β-cyclodextrin is dissolved completely. To this solution, 9.96 g of carbonyl di-imidazole (61.42 mmol) is added, and the reaction mixture is maintained at 100°C for 4 hours to allow condensation polymerization. After

completion of the reaction, the resulting transparent, hyper–cross-linked cyclodextrin polymer is coarsely ground, and excess deionized water is added to remove the solvent. Further purification is carried out using Soxhlet extraction with ethanol to eliminate any unreacted materials and by-products. The purified product, obtained as a white powder, is dried overnight in an oven at 60°C and then finely ground using a mortar and pestle. The powder is subsequently dispersed in water, and the colloidal fraction that remains suspended is collected and lyophilized. The final nanosponges obtained are typically spherical in shape and fall within the submicron size range.

3.Solvent method [32-33]:

Mix the polymer with a suitable solvent, mainly in a polar aprotic solvent such as dimethylformamide (DMF), dimethyl sulfoxide (DMSO). Then add this mixture to cross linker in a exceed quantity, the ratio for cross linker/ molar ratio is preferred as 1:4. The reaction carried out at temperature ranging from 100c to the reflux temperature of the solvent, for time ranging from 1 to 48 hr. The cross linkers which may preferred are dimethyl carbonate and carbonyl diimidazole. There action is completed and solution is allowed to cool at room temperature then product is added to large excess of bi-distilled water and product is recovered by filtration under vacuum and subsequently purify by prolonged Soxhlet extraction with ethanol. Finally, product is dried under vacuum and grinded in a mechanical mill to obtain homogeneous powder.

4.Ultrasound- Assisted Synthesis [32-33]

In this method nanosponges can be obtained by reacting polymers with cross- linkers in the absence of solvent and under sonication. The obtained nanosponges will be spherical, uniform in size and smaller than 5 microns. In this method di-phenyl carbonate (or) pyromellitic anhydride is used as cross-linker. Here, mix the polymer and cross- linker in a flask. Place the flask in an ultrasound bath filled with water and heat it to 90oc and sonicate for 5 hours. Then, the solid was ground in a mortar and Soxhlet extraction with ethanol to remove either impurity (or) unreacted polymer. After Purification nanosponges were stored at 25oc.

FACTORS INFLUENCE NANOSPONGES: [34-36]

1.Type of Polymer:

The kind of polymer used, especially different types of cyclodextrins, plays an important role in how well the drug fits inside the nanosponge. It affects drug loading, stability, and overall performance.

2.Type and Amount of Cross-linker:

Cross-linkers help form the structure of nanosponges. If more cross-linker is used, the structure becomes tighter and more rigid, which can slow down how the drug is released.

3.Polymer-to-Cross-linker Ratio:

The balance between polymer and cross-linker is very important. The right ratio helps in forming a porous structure that can hold and release the drug effectively.

4.Method of Preparation:

The way nanosponges are prepared (such as solvent method or melt method) can change their size, shape, and uniformity, which in turn affects their efficiency.

5.Reaction Temperature and Time:

Temperature and time during preparation influence how well the nanosponges are formed. Too much heat or long reaction time can damage the drug or polymer.

6.Nature of the Drug:

The drug's properties, like its size and whether it dissolves in water or fat, affect how easily it can be loaded into nanosponges and how it will be released.

7.Type of Solvent:

The solvent used during preparation helps dissolve the materials and allows the reaction to happen properly. It can influence the final structure and quality of nanosponges.

8.Stirring and Mixing Conditions:

Proper mixing is needed to get uniform particles. Poor mixing can lead to clumping or uneven nanosponges.

9.pH of the Medium:

The pH can affect both the drug and the nanosponge. It plays a role in drug stability and how the drug interacts with the polymer

10.Drug-to-Polymer Ratio:

This ratio decides how much drug can be loaded. Too much drug may not get fully trapped inside the nanosponges.

11.Drying Method:

The way nanosponges are dried can affect their size, stability, and flow properties.

Post-preparation Processing:

Proper washing and purification are important to remove unwanted chemicals and ensure the nanosponges are safe and effective.

ADVANTAGES OF NANOSPONGES[37-39]

Nanosponges have emerged as a promising nanocarrier system in drug delivery due to their unique porous structure and versatility. Their ability to improve drug performance while maintaining safety makes them highly attractive for pharmaceutical applications.

1. Improved Solubility

One of the most important advantages of nanosponges is their ability to enhance the solubility of poorly water-soluble drugs. By entrapping drug molecules within their nano-sized cavities, they facilitate better interaction with aqueous environments, which ultimately improves dissolution and absorption

2. Controlled and Sustained Drug Release

Nanosponges are formed by a cross-linked polymeric network that allows drugs to be released in a controlled manner over time. This sustained release behavior helps maintain consistent drug levels in the body and reduces the need for frequent dosing .

3. Enhanced Bioavailability

Because of their impact on solubility and release patterns, nanosponges can significantly improve the bioavailability of drugs that otherwise show poor absorption or rapid degradation

4. High Drug Loading Capacity

Their highly porous structure provides ample space for drug entrapment. This enables nanosponges to carry a relatively higher amount of

drug compared to many conventional delivery systems

5. Protection of Drug from Degradation

Nanosponges act as protective carriers by shielding drug molecules from environmental factors such as light, heat, and oxidation. This improves the stability of sensitive drugs and can extend their shelf life

6. Potential for Targeted Drug Delivery

With suitable surface modifications, nanosponges can be designed to deliver drugs to specific sites in the body. This targeted approach helps in maximizing therapeutic effects while minimizing unwanted exposure to healthy tissues

7. Reduced Side Effects

The combination of controlled release and targeted delivery contributes to a reduction in drug-related side effects. By avoiding sudden spikes in drug concentration, nanosponges help improve overall treatment safety.

8. Versatility in Drug Encapsulation

Nanosponges are capable of incorporating both hydrophilic and lipophilic drugs. This flexibility allows them to be used with a wide variety of pharmaceutical compounds .

9. Biocompatibility and Safety

Most nanosponges, especially those based on cyclodextrins, are known for their biocompatibility and low toxicity. This makes them suitable for long-term therapeutic use

10. Flexibility in Formulation

Nanosponges can be easily incorporated into different dosage forms such as gels, creams, tablets, and capsules. This adaptability makes them useful for multiple routes of administration

11. Better Patient Compliance

By reducing dosing frequency and minimizing side effects, nanosponges contribute to improved patient adherence, which is a key factor in successful therapy

Disadvantages of Nanosponges[40,41]

1.Complex Preparation Methods: The synthesis of nanosponges often involves crosslinking reactions that require precise control of conditions, making the process relatively complex.

2.Use of Organic Solvents: Some preparation methods involve solvents like DMF or DMSO, which may pose toxicity concerns if not completely removed.

3.Limited Drug Loading for Large Molecules: Nanosponges are more suitable for small molecules; large molecular weight drugs may not fit efficiently into their cavities.

4.Potential Residual Toxicity: Unreacted crosslinkers or residual chemicals may lead to toxicity if purification is not adequate.

Characterization Of Nanosponges [43-46]

1.Particle Size and Distribution: Determines how uniform the nanosponges are, which affects drug release rate and skin/follicular penetration.

2.Surface Morphology (SEM/TEM):Used to observe the shape and confirm the porous, sponge-like structure at nanoscale.

3.Fourier Transform Infrared Spectroscopy (FTIR):Helps identify functional groups and ensures there is no chemical incompatibility between drug and polymer.

3.Differential Scanning Calorimetry (DSC):Evaluates thermal behaviour and confirms drug incorporation by detecting changes in melting patterns.

4.X-ray Diffraction (XRD):Determines whether the drug becomes amorphous after encapsulation, which can improve solubility.

5.Drug Loading and Entrapment Efficiency: Indicates how much drug is successfully incorporated into the nanosponge system.

6.In-vitro Drug Release Studies: Assesses the release pattern of the drug, especially for controlled and sustained delivery.

7.Zeta Potential: Measures surface charge and predicts the physical stability of nanosponges in dispersion.

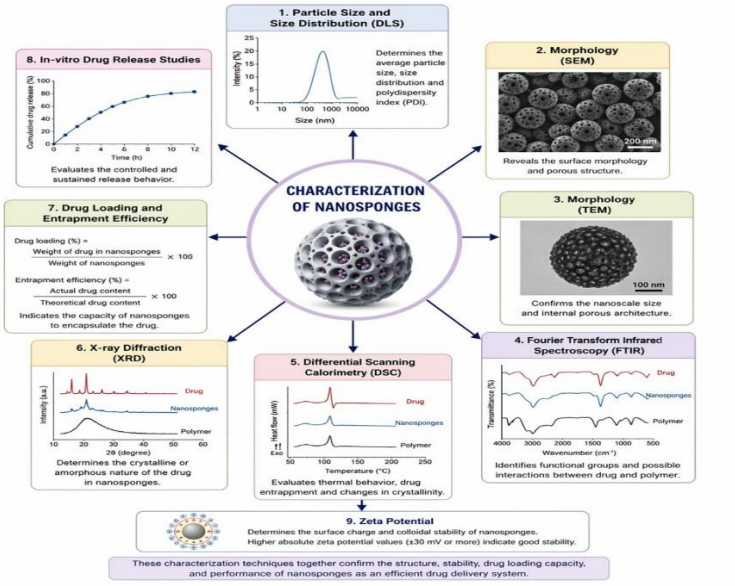

Fig.5. Characterization Of Nanosponges

Applications Of Nanosponges[5,37,42]

Nanosponges are highly cross-linked, porous nanocarriers that have gained significant attention due to their ability to encapsulate diverse therapeutic agents and modulate drug release. Their unique three-dimensional structure, large surface area, and tunable properties make them suitable for a wide range of pharmaceutical and biomedical applications.

*** Advanced Drug Delivery Systems**

Nanosponges function as versatile carriers capable of incorporating both hydrophilic and lipophilic drugs. Their adaptable structure allows formulation into various dosage forms such as oral, topical, and parenteral systems. Additionally, the polymeric network protects sensitive drugs from chemical and enzymatic degradation, thereby enhancing stability and therapeutic effectiveness.

*** Enhancement of Solubility and Bioavailability**

A major advantage of nanosponges is their ability to improve the solubility of poorly water-soluble

drugs. By entrapping drug molecules within their porous structure, they enhance dissolution rate and bioavailability, addressing a key limitation in drug formulation.

*** Controlled and Sustained Drug Release**

Nanosponges act as drug reservoirs, releasing the encapsulated drug in a controlled and sustained manner. This ensures prolonged therapeutic action, reduces dosing frequency, and improves patient compliance.

*** Targeted and Site-Specific Drug Delivery**

Due to their nanoscale size and modifiable surface characteristics, nanosponges can localize at specific sites within the body. This targeted delivery enhances drug concentration at the desired site while minimizing systemic exposure and associated side effects.

*** Topical Drug Delivery and Dermal Applications**

Nanosponges are particularly effective in topical formulations as they tend to localize within the stratum corneum and skin appendages. This enhances drug retention in the skin and limits systemic absorption, making them highly suitable for dermatological conditions.

Advanced and Emerging Mechanistic Applications

Recent developments have led to the design of stimuli-responsive nanosponges that can release drugs in response to environmental triggers such as pH, temperature, or enzymatic activity. This enables more precise and controlled drug delivery, particularly in conditions like acne where the local microenvironment can be exploited. Nanosponges also provide controlled drug permeation without disrupting the skin barrier, preserving its structural integrity. Their highly cross-linked structure minimizes burst release, ensuring uniform drug release kinetics and improved safety. Additionally, nanosponges support multifunctional delivery by enabling the co-encapsulation of multiple therapeutic agents, allowing simultaneous targeting of different pathogenic pathways. Their high surface area enhances interaction with the skin, improving drug retention and local bioavailability.

*** Other Pharmaceutical and Biomedical Applications**

Beyond dermatological use, nanosponges have demonstrated potential in antimicrobial and antifungal therapy by providing sustained drug release. In cancer treatment, they are being explored as carriers for controlled and targeted delivery of chemotherapeutic agents, aiming to improve therapeutic outcomes while reducing toxicity. Nanosponges are also capable of delivering biomolecules such as proteins and enzymes, protecting them from degradation. In the cosmetic field, they are used for controlled release of active ingredients like vitamins, antioxidants, and fragrances, enhancing product stability and performance. Emerging research further highlights their applications in biosensing, environmental remediation, and advanced therapeutic systems.

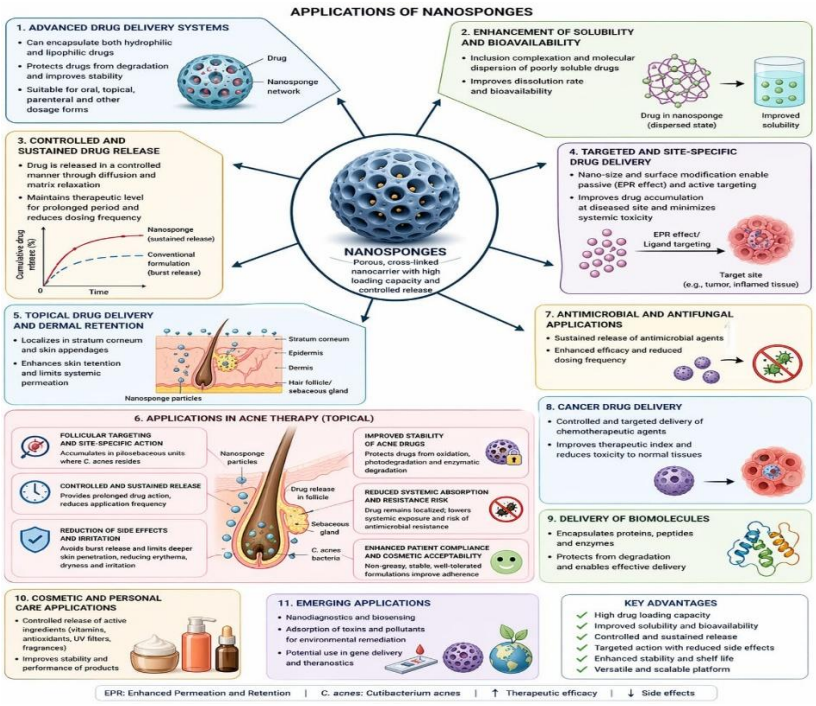

Fig.6. Applications Of Nanosponges

Future Perspectives Of Nanosponges In Acne Therapy[47-49]

Nanosponges are gaining attention as a promising drug delivery platform with the potential to improve current approaches to acne treatment. Future developments are likely to focus on designing stimuli-responsive nanosponge systems that can release drugs in response to local conditions such as pH changes, enzymatic activity, or oxidative stress within acne-affected skin. Such approaches may help in delivering drugs more precisely to the site of action, thereby improving effectiveness while limiting unnecessary exposure. Enhancement of targeting efficiency through surface modification is another area of growing interest. By incorporating suitable functional groups or bio adhesive materials, nanosponges can be tailored to interact more effectively with the skin and localize within the pilosebaceous unit. This could result in higher drug concentration at the affected site and reduced systemic side effects. There is also increasing scope for combination-based nanosponge systems, where multiple therapeutic agents are incorporated into a single carrier. This strategy may help address different aspects of acne pathogenesis simultaneously, such as microbial growth, inflammation, and excess sebum production, leading to improved therapeutic outcomes. In addition, combining nanosponges with advanced topical formulations like hydrogels or nanoemulgels may further enhance drug penetration and retention in the skin. Despite these advantages, challenges such as large-scale production, consistency in formulation, long-term stability, and safety evaluation still need to be carefully addressed. With continued research and refinement, nanosponges are expected to evolve into more effective, targeted, and patient-friendly systems, offering improved options for the management of acne vulgaris.

CONCLUSION:

Acne vulgaris is a complex and widely occurring skin condition that remains challenging to manage effectively, even with the range of treatments currently available. Common issues such as poor drug penetration into the skin, irritation, instability of formulations, and increasing antibiotic resistance highlight the need for better and more reliable therapeutic approaches. Nanosponges have emerged as a promising alternative in this regard. Their porous, three-dimensional structure allows them to carry different types of drugs and release them in a controlled manner. When applied to the skin, they can remain localized and deliver the drug directly to the affected area, which may improve treatment effectiveness while reducing side effects. Overall, nanosponges offer a practical and adaptable approach to drug delivery in acne therapy. With continued research and refinement, they have the potential to improve current treatment outcomes and provide more convenient and patient-friendly options for managing acne.

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