INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

OPEN ACCESS

**Review Paper**

# Advanced Drug Delivery Strategies for Targeted Anti-inflammatory Therapy

**Atul Pratap*, Saniyasnain, Preeti Kuniyal**

*HIMT College of Pharmacy, Knowledge Park-1, Greater Noida-201310, Uttar Pradesh, India.*

ARTICLE INFO

Published: 23 Sept 2026
Keywords:
Anti-inflammatory drugs, Drug delivery systems, Nanotechnology, Liposomes, Hydrogels, Targeted delivery, Nanoparticles, Controlled release
DOI:
10.5281/zenodo.22915842

## ABSTRACT

Inflammation is a defensive response to infection, injury, or harmful stimuli. Acute inflammation supports healing and immunity, but chronic inflammation can lead to serious conditions such as rheumatoid arthritis, inflammatory bowel disease, asthma, cardiovascular disease, diabetes, neurodegenerative disorders, and cancer. Conventional treatments include NSAIDs, cortisone or steroids, and immune-suppressants, but these have limitations like poor absorption, lack of site targeting, side effects, frequent dosing, and poor patient compliance.Materials and MethodsRecent advancements in pharmaceuticals have introduced sophisticated drug delivery systems designed to maximize therapeutic effectiveness and minimize adverse effects. Examples include nanoparticles, liposomes, microspheres, hydrogels, nano-emulsions, dendrimers, transdermal systems, and targeted carriers. These systems aim to deliver anti-inflammatory agents directly to sites of inflammation.ResultsThe use of advanced drug delivery systems demonstrates enormous promise in the management of inflammation. These systems increase the stability of drugs during storage, prolong the circulation time of therapeutic agents in the body, and enhance the delivery of the intended dose to the specific site of inflammation. They also provide controlled release from their storage forms and allow targeted action at inflamed sites. Furthermore, novel nanotechnology-based and stimuli-responsive materials create new possibilities for personalized and effective methods of managing inflammation, thereby offering significant improvements over conventional therapies.ConclusionRecent reviews highlight the pathophysiology of inflammation, limitations of conventional therapies, and the potential of emerging smart drug delivery systems. Particular emphasis is placed on nanotechnology-based targeted delivery, clinical applications, challenges of current therapies, and future prospects for anti-inflammatory treatments.

***Corresponding Author:** Atul Pratap
**Address:** *HIMT College of Pharmacy, Knowledge Park-1, Greater Noida-201310, Uttar Pradesh, India.*
**Email** ✉: pratapatul348@gmail.com
**Relevant conflicts of interest/financial disclosures**: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## INTRODUCTION

The body produces reactive substances to protect itself against foreign particles in an inflammatory response. An immune response will occur after you become infected with microbes, injured, or exposed to toxins. This marks the beginning of the body's first line of defense and assists in eliminating harmful stimuli and commencing repair to damaged tissue. [1,2,3] The inflammatory response is actually a very intricate process involving several physiological changes (blood vessel dilation, recruitment of various immune cell types) and the activation of an array of chemical-mediators post exposure (cytokines, prostaglandins, histamine/leukotrienes). [4,5]

There are two common forms of Inflammation: Acute & Chronic. Acute Inflammation occurs for a short period of time and has the classic symptoms of being Red, Swollen, Hot, Painful and also limiting the use of the area of the body that is swollen and inflamed. Acute Inflammation will usually go away as soon as the Stimulus that caused the Injury gets taken away. Chronic Inflammation lasts longer than Acute Inflammation and causes or contributes to the progression of many types of Chronic Disease such as; Arthritis, Cardiovascular Disease, Asthma, Inflammatory Bowel Disease, Psoriasis, Alzheimer's Disease and Cancer. [6,7,8]

Traditional anti-inflammatory medications have an important role for treating inflammatory diseases. While NSAIDs block the action of the cyclooxygenase enzymes and decrease the production of prostaglandin, corticosteroids block the immune response and the action of inflammatory chemicals. Although these drugs are very effective, there are numerous side effects associated with their use including irritation of the stomach lining (ulcerative gastritis), toxicity to the kidney (nephrotoxicity), suppression of the immune system (immunosuppression), elevated blood pressure (hypertension), and liver toxicity (hepatotoxicity). Additionally, since traditional dosage forms of medication do not have sufficient site-specific delivery capabilities, there are lower levels of effectiveness at the site of action and greater levels of side effects throughout other areas of the body. [9,10,11]

In order to overcome these limitations, efficient drug delivery systems have become of significant interest in recent years, as they aim to enhance drug targeting, improve adverse effects, and increase bioavailability and/or provide a continuous or controlled release of the drug. Nanocarriers and targeted delivery systems using nanotechnology have the greatest potential for use as therapeutic agents because they enable the direct and efficient delivery of therapeutic agents to areas of inflammation. [12,13,14]

The development of modern drug delivery systems has transformed the field of inflammation therapy by enabling precise and personalized treatment strategies. Therefore, understanding the role of advanced delivery systems is essential for improving the safety and effectiveness of anti-inflammatory therapy. [15,16]

## 2. Pathophysiology of Inflammation

The inflammatory response starts when immune cells such as macrophages, neutrophils, mast cells, and dendritic cells are activated. These cells secrete inflammatory mediators including histamine, cytokines, prostaglandins, tumor necrosis factor-alpha TNF-α), and interleukins. [17,18]

### 2.1 Mechanism of Inflammatory Response

The inflammatory response starts when immune cells such as macrophages, neutrophils, mast cells, and dendritic cells are activated. These cells secrete inflammatory mediators including histamine, cytokines, prostaglandins, tumor

necrosis factor-alpha TNF-α), and interleukins. [19,20]

The major steps involved in inflammation include:

[1] Detection of harmful stimuli as the inflammatory response initiates when immune cells recognize damaging substances including pathogens, toxins, allergens, or damaged tissues via specific receptors located on their surface. [21]

[2] Release of inflammatory mediators on detecting a harmful stimulus, immune cells secrete a range of chemical mediators such as histamine, cytokines, prostaglandins, and leukotrienes that trigger and modulate the inflammatory response. [22]

[3] Vasodilation and heightened vascular permeability cause blood vessels in the affected region to widen and become more porous, facilitating the movement of plasma proteins, nutrients, and immune cells from the bloodstream into the injured tissues. [23]

[4] The movement of white blood cells especially neutrophils and macrophages to the site of injury involves chemotaxis, a process by which these cells are drawn to areas of inflammation to eliminate pathogens and clear away dead cells. [24]

[5] Pathogen and damaged cell elimination as once activated, immune cells will phagocytose organisms that are infectious and produce toxins to create tissue destruction and will also phagocytose dead portions of tissue preventing additional tissue destruction and spread of infection. [25]

[6] Tissue Healing after removal of the noxious (harmful) agent, the body initiates tissue healing responses by means of cell regeneration, collagen production and restoring normal tissue structure and function. [26]

Although acute inflammation typically has a positive effect in terms of providing protection, the development of chronic inflammatory disease occurs when the body cannot control or cease the inflammatory process.

### 2.2 Function of Cytokines and Other Mediators of Inflammation

Cytokines are small protein-based signalers that modulate or regulate the body's immunological response and its ability to carry out an inflammatory response. Some of the key cytokines that are involved in the inflammatory process include the following:

- **Interleukin 1 (IL-1):** This is mainly a pro-inflammatory cytokine released by activated macrophages. It is an important modulator of the initiation of the inflammatory process as it is responsible for initiating fever, promoting the activation of leukocytes and stimulating other pro-inflammatory mediators to produce inflammation. [27]
- **Interleukin 6 (IL-6):** IL-6 has both an acute and chronic involvement in the inflammatory process. It is responsible for differentiating immune cells, stimulating antibody production, and inducing fever and tissue inflammation in both infectious and autoimmune diseases. [28]
- **Tumor necrosis factor alpha (TNF-α):** TNF-α is a primary cytokine responsible for causing systemic inflammation. It causes increased vascular permeability, activation of immune cells, and is associated with the long-term destructive effects of chronic inflammatory disease processes, such as rheumatoid arthritis and inflammatory bowel diseases, [29]
- **Interferons:** Interferons are cytokines produced as a consequence of viral infections. They play an important role in regulating the body's immunological response by activating

immune cells and preventing viruses from replicating within infected tissues. [30]

Some other key inflammatory mediators that induce pain and inflammation are:

- **Histamine:** released primarily from mast cells (a type of white blood cell involved in allergic reactions) and basophils (type of white blood cell that is part of the immune system), histamine is produced in response to inflammatory stimuli in the body, and functions to widen blood vessels, increasing their permeability. This results in redness, swelling, and itching (i.e., the foreign substance or pathogen has entered your body). [31]
- **Bradykinin:** Bradykinin, a peptide, is another key mediator of pain and inflammatory reactions, which promotes vasodilation (widening of blood vessels) and increases vascular permeability, which results in swelling and tenderness in the tissue. [32]
- **Prostaglandins:** Prostaglandins (lipid-based mediators) are synthesized from arachidonic acid (an omega-6 fatty acid found in the phospholipid bilayer of human cells) through the action of cyclooxygenase enzymes and are primarily responsible for producing pain, fever, and inflammation. NSAIDs exert their pain-relieving effects by blocking the action of cyclooxygenase enzymes and thereby inhibiting the production of prostaglandins. [33]
- **Leukotrienes:** Leukotrienes are inflammatory mediators produced primarily by leukocytes (white blood cells) and are involved in a number of inflammatory diseases, such as asthma, and allergic reactions. They cause bronchoconstriction (narrowing of the airways in the lungs), increased mucus production in the respiratory tract and the recruitment of immune cells to the site of inflammation. [34]
- **Nitric oxide (NO):** Nitric oxide is a signaling molecule that is produced in the body and functions to regulate the tone (constriction/dilation) of blood vessels and the immune response. Excess levels of NO during inflammation can lead to collateral tissue damage and oxidative stress. [35]

### 2.3 Common Inflammatory Disorders

There are numerous diseases that are related to chronic inflammation, which include

- **Rheumatoid arthritis** (a long-term autoimmune inflammatory disease that is predominantly an illness affecting the joints with sign symptoms of pain, swelling, stiffness and ultimately destruction of cartilage and bone); the persistent inflammation from rheumatoid arthritis can have a negative impact on the body's other organs, including the lungs and heart. [36]
- **Osteoarthritis** is a progressive joint disease that is associated with the development of chronic low-grade inflammation that contributes to the degrading of cartilage, leading to joint pain, decreased range of motion and stiffness in individuals who are older. [37]
- **Asthma** is a chronic inflammatory condition of the airways that is caused by inflammation around the bronchial tubes, narrow airways, mucus production and difficulty in breathing. It can occur in response to allergens, infectious agents, and/or environmental factors. [38]
- **Psoriasis** is a chronic inflammatory dermatologic condition associated with an exaggerated immune response leading to rapid proliferation of skin cells resulting in red, scaly, and itchy lesions of the skin. [39]
- **Inflammatory bowel disease** includes Crohn's disease and ulcerative colitis, in

which the gastrointestinal tract is inflamed for long periods of time, resulting in symptoms such as belly pain, diarrhea, rectal bleeding and weight loss. [40]

- **Cardiovascular diseases** Chronic inflammation causes endothelial damage, plaque formation and atherosclerosis, thereby contributing to an increased risk of a heart attack or stroke. [41]
- **Diabetes mellitus:** Chronic inflammation leads to insulin resistance and impaired glucose metabolism in people with type 2 diabetes (diabetes mellitus), resulting in increased blood sugar and complications associated with it. [42]
- **Neurodegenerative disorders:** Long-term inflammation in the nervous system is associated with neurodegenerative disorders like Alzheimer's disease and Parkinson's disease, where inflammatory mediators cause neuronal death and cognitive impairment. [43]
- **Cancer:** Long-term inflammation causes DNA damage and stimulates abnormal cell growth, and creates a tumor-promoting microenvironment, leading to the emergence and growth of cancer. [44]

The rise in the number of people with these diseases has caused an increase in the research and development of safe and effective new anti-inflammatory therapies.

## 3. Conventional Anti-inflammatory Therapies

### 3.1 Non-Steroidal Anti-inflammatory Drugs (NSAIDs)

NSAIDs continue to be among the most commonly prescribed anti-inflammatory drugs due to their capacity to block cyclooxygenase enzymes and reduce prostaglandin production. Commonly used drugs like ibuprofen, diclofenac, naproxen, aspirin, and celecoxib help alleviate pain, swelling, and fever linked to inflammatory conditions. [45]

Despite their therapeutic benefits, NSAIDs are associated with several limitations including gastrointestinal ulceration, renal toxicity, cardiovascular complications, and short biological half-lives. Frequent administration is often necessary to maintain therapeutic drug concentrations, which may further increase the risk of adverse effects. [46]

### 3.2 Corticosteroids

Corticosteroids such as prednisolone and dexamethasone suppress inflammatory responses by inhibiting cytokine production and immune cell activation. [47,48]

**Adverse Effects**

- Immunosuppression
- Osteoporosis
- Hyperglycemia
- Weight gain
- Hypertension

### 3.3 Immunosuppressive Agents

Immunosuppressive drugs such as methotrexate, cyclosporine, and azathioprine are used in autoimmune inflammatory diseases. [49,50]

**Limitations**

- Increased risk of infections
- Organ toxicity
- Bone marrow suppression
- Long-term safety concerns

### 3.4 Limitations of Conventional Dosage Forms

Traditional dosage forms such as tablets, capsules, and injections often suffer from: [51]

- Poor site specificity
- Rapid drug clearance

- Low bioavailability
- Dose fluctuations
- Systemic adverse effects

These limitations have spurred the creation of more sophisticated drug delivery methods.

## 4. Advanced Anti-inflammatory Drug Delivery Systems

These systems are engineered to enhance the pharmacokinetic and pharmacodynamic properties of anti-inflammatory medications. [52]

### 4.1 Nanoparticles

Nanoparticles: Due to their distinctive physicochemical properties, nanoparticles can penetrate inflamed tissues more effectively than traditional dosage forms. Their surface can also be altered to enhance targeting efficiency, circulation time, and interaction with biological membranes. [53]

Nanoparticles are colloidal carriers whose particle sizes fall within the range of 1 to 1000 nanometers. They are commonly employed in targeted anti-inflammatory treatments due to their compact size and improved permeability. The distinct physicochemical characteristics of nanoparticles enable them to penetrate inflamed tissues more effectively than traditional drug delivery methods. Their surface can also be altered to enhance targeting efficiency, circulation time, and interaction with biological membranes. [54,55]

Types of Nanoparticles The unique physicochemical properties of nanoparticles allow them to penetrate inflamed tissues more efficiently than conventional dosage forms. Their surface can also be modified to improve targeting efficiency, circulation time, and interaction with biological membranes. [56]

Polymeric Nanoparticles The unique physicochemical properties of nanoparticles allow them to penetrate inflamed tissues more efficiently than conventional dosage forms. Their surface can also be modified to improve targeting efficiency, circulation time, and interaction with biological membranes. [57,58]

These are prepared using biodegradable polymers such as PLGA, chitosan, and alginate.

#### Advantages

- Controlled drug release
- Improved stability
- Enhanced bioavailability
- Reduced toxicity

Solid Lipid Nanoparticles The unique physicochemical properties of nanoparticles allow them to penetrate inflamed tissues more efficiently than conventional dosage forms. Their surface can also be modified to improve targeting efficiency, circulation time, and interaction with biological membranes. [59,60]

These nanoparticles contain solid lipids and offer better drug stability and biocompatibility. The unique physicochemical properties of nanoparticles allow them to penetrate inflamed tissues more efficiently than conventional dosage forms. Their surface can also be modified to improve targeting efficiency, circulation time, and interaction with biological membranes. [61]

#### Applications

- Arthritis treatment
- Topical anti-inflammatory therapy
- Pulmonary drug delivery

### 4.2 Liposomes

Liposomes have gained considerable importance in pharmaceutical research because they can encapsulate a wide variety of therapeutic agents while reducing systemic toxicity. Their phospholipid structure closely resembles biological membranes, thereby improving compatibility with body tissues. [62]

Liposomes are spherical structures made up of phospholipid bilayers. They are capable of enclosing both water-soluble and fat-soluble drugs. Liposomes have become increasingly significant in pharmaceutical research due to their ability to encapsulate a broad range of therapeutic agents while minimizing systemic toxicity. Their phospholipid structure closely mimics biological membranes, enhancing compatibility with body tissues. [63,64]

Advantages of Liposomes Liposomes have gained considerable importance in pharmaceutical research because they can encapsulate a wide variety of therapeutic agents while reducing systemic toxicity. Their phospholipid structure closely resembles biological membranes, thereby improving compatibility with body tissues. [65]

- Biocompatibility
- Reduced toxicity
- Site-specific delivery
- Sustained release

**Therapeutic Applications**

Many clinical studies have explored the use of liposomes to treat rheumatoid arthritis, psoriasis, and inflammatory bowel diseases. They are becoming increasingly important to pharmaceutical research due both to their ability to carry a broad range of therapeutic agents and reduce systemic toxicity when used as delivery vehicles. Another advantage of liposomes is that their phospholipid structure is similar to that of biological membranes, which may improve their compatibility with human body tissues. [66,67]

**4.3 Microspheres and Microcapsules**

Microspheres are tiny spherical particles designed to deliver drugs in a controlled and sustained manner. [68,69]

**Benefits**

- Extended drug release
- Reduced dosing frequency
- Improved patient compliance

**Clinical Applications**

- Injectable anti-inflammatory formulations
- Oral sustained-release dosage forms

**4.4 Hydrogels**

Hydrogels are increasingly being investigated for localized drug delivery because of their high water content and soft tissue-like characteristics. These systems can provide prolonged retention of therapeutic agents at the site of inflammation while minimizing systemic exposure. [70]

Hydrogels are three-dimensional polymer networks that can absorb significant quantities of water. Hydrogels are gaining more attention for localized drug delivery due to their high water content and tissue-like softness. These systems can maintain sustained release of therapeutic agents at the site of inflammation while reducing systemic exposure. [71,72]

**Types**

- **Injectable hydrogels:** Due to their high water content and tissue-like softness, hydrogels are gaining attention for targeted drug delivery. These systems can help maintain a sustained presence of therapeutic agents at the site of inflammation while reducing systemic exposure. [73]
- **Thermosensitive hydrogels:** Hydrogels are gaining attention for targeted drug delivery due to their high water content and tissue-like softness. These systems can maintain sustained delivery of therapeutic agents to the site of inflammation while reducing systemic exposure. [74]
- **pH-sensitive hydrogels:** Hydrogels are gaining attention for targeted drug delivery

due to their high water content and tissue-like softness. These systems can maintain a sustained presence of therapeutic agents at the site of inflammation while reducing systemic exposure. [75]

**Advantages**

- Localized drug delivery
- Controlled release
- Excellent biocompatibility

Hydrogels are commonly used in wound healing and topical inflammation management. Inflammation is not only a protective biological mechanism, but also a highly coordinated process that determines how effectively the body responds to tissue injury and infection. The intensity and duration of the inflammatory response often influence the progression and outcome of several acute and chronic disorders. [76]

**4.5 Nanoemulsions**

Nanoemulsions are thermodynamically stable systems containing oil, water, surfactants, and co-surfactants. [77]

**Advantages**

- Improved solubility
- Better skin penetration
- Enhanced bioavailability

**Applications**

- Topical delivery of NSAIDs
- Ocular inflammation treatment
- Dermal inflammatory disorders

**4.6 Transdermal Drug Delivery Systems**

These systems administer medication through the skin via patches, gels, or films. [78]

**Benefits**

- Avoid first-pass metabolism
- Sustained drug release
- Better patient compliance
- Reduced gastrointestinal toxicity

**Applications**

- Diclofenac patches
- Ketoprofen gels
- Lidocaine patches

**4.7 Dendrimers**

Dendrimers are highly branched nanostructures with controlled architecture. [79]

**Advantages**

- High drug loading capacity
- Improved solubility
- Controlled release

Dendrimers are increasingly explored for targeted delivery of anti-inflammatory agents.

**4.8 Targeted and Smart Drug Delivery Systems**

Targeted drug delivery systems transport drugs specifically to inflamed tissues. [80]

**Ligand-Targeted Systems**

These systems use antibodies, peptides, or receptors for selective targeting.

**Stimuli-Responsive Systems**

These systems deliver drugs in reaction to particular stimuli such as:

- pH changes
- Temperature
- Enzymes
- Magnetic fields
- Light

Smart systems minimize systemic exposure and improve therapeutic efficacy.

## 5. Role of Nanotechnology in Inflammation Treatment

Role of Nanotechnology in Inflammation Treatment Inflammation is not only a protective biological mechanism, but also a highly coordinated process that determines how effectively the body responds to tissue injury and infection. The intensity and duration of the inflammatory response often influence the progression and outcome of several acute and chronic disorders. [81]

Nanotechnology has transformed the treatment of inflammatory diseases through its ability to deliver drugs with precision and targeting. Recent progress in nanotechnology has greatly enhanced the accuracy and efficacy of anti-inflammatory treatments. Nanocarriers are currently being engineered with multifunctional capabilities to enable simultaneous targeting, imaging, and controlled drug delivery. [82,83]

### 5.1 Nanocarriers

Nanocarriers protect drugs from degradation and improve their circulation time. [84]

Common nanocarriers include:

- Polymeric nanoparticles
- Lipid nanoparticles
- Liposomes
- Dendrimers
- Carbon nanotubes

### 5.2 Surface Modification

Surface modification improves targeting efficiency and reduces immune recognition. [85]

Examples include:

- PEGylation
- Antibody conjugation
- Ligand attachment

### 5.3 Site-Specific Targeting

Nanotechnology enables selective accumulation of drugs at inflamed tissues through passive and active targeting. [86]

**Advantages**

- Reduced toxicity
- Lower dose requirements
- Enhanced therapeutic outcomes

Nanotechnology formulations have been shown to be effective in treating several diseases, including rheumatoid arthritis, psoriasis, and inflammatory bowel disease.

## 6. Current Research and Applications

Over the past ten years, the number of studies on new delivery systems has increased at an unprecedented rate. [87]

### 6.1 Studies Says

The use of nanotechnology-based delivery systems has resulted in improved efficacy in many studies. [88]

Examples include:

- Curcumin-loaded nanoparticles for arthritis
- Liposomal corticosteroids for inflammatory bowel disease
- Hydrogel-based wound healing systems
- Nanoemulsion formulations for topical inflammation

### 6.2 Approved Formulations

Several advanced delivery systems have already been granted clinical approval. [89]

Examples include:

- Liposomal diclofenac formulations
- Transdermal anti-inflammatory patches
- Controlled-release corticosteroid injections

### 6.3 Ongoing Clinical Trials

Current clinical trials focus on: [90]

- Targeted biologic delivery

- Nanoparticle-mediated therapy
- Smart hydrogels
- Gene delivery systems

The growing number of clinical studies suggests significant future potential for these systems.

## 7. Advantages and Limitations

### 7.1 Advantages of Advanced Drug Delivery Systems [91,92,93]

**Lower Toxicity**
Targeted delivery reduces healthy tissue exposure and lowers negative effects.

**Improved Patient Compliance**
Controlled release systems decrease dosing frequency.

**Increased Bioavailability**
New carriers improve the absorption and stability of drugs.

**Controlled Drug Release**
Sustained release systems provide longer periods of therapeutic drug levels.

**Site-Specific Targeting**
Targeted delivery systems transport drugs directly to inflamed tissues.

### 7.2 Limitations [94,95]

**Stability Challenges –**
Physical or Chemical Stability has been shown to be inadequate with some nanocarriers.

**Costly Manufacturing –**
Advanced formulations often require specialized machinery and processing technology.

**Regulatory Compliance –**
Formulations that are complex often come with stringent regulatory requirements for Safety (including Efficacy).

**Safety/Ecotoxicity –**
Safety (Including Long-term Toxicity) associated with certain nanomaterials are still under investigation.

## 8. FUTURE PERSPECTIVES

The future of anti-inflammatory drug delivery systems is highly promising.

### 8.1 Personalized Medicine

Personalized therapy based on patient genetics and disease profile is expected to improve treatment outcomes. [96]

### 8.2 Artificial Intelligence in Drug Delivery

Artificial intelligence can assist in: [97]

- Drug formulation design
- Predicting drug release patterns
- Optimizing targeting strategies
- Clinical decision-making

### 8.3 Advanced Biomaterials

Novel biomaterials with improved biocompatibility and responsiveness are under development. [98]
Examples include:

- Smart polymers
- Biodegradable nanomaterials
- Hybrid delivery systems

### 8.4 Gene and Cell-Based Therapy

Gene delivery and stem cell-based systems may provide long-term treatment options for chronic inflammatory diseases. [99]

### 8.5 Future Scope in Healthcare

Future anti-inflammatory therapies are expected to become: [100]

- More targeted
- Safer

- Cost-effective
- Personalized
- Minimally invasive

Ongoing research and technological progress will be essential in enhancing patient care.

## CONCLUSION

Inflammation is a key factor in the onset of numerous acute and chronic diseases. While traditional anti-inflammatory drugs continue to play a key role in clinical use, their drawbacks including inadequate targeting, low bioavailability, and systemic toxicity have spurred the creation of more sophisticated drug delivery systems. [101,102] Inflammation is not only a protective biological mechanism, but also a highly coordinated process that determines how effectively the body responds to tissue injury and infection. The intensity and duration of the inflammatory response often influence the progression and outcome of several acute and chronic disorders. [103]

New methods of delivering drugs - including nanoparticles, liposomes, hydrogels, microspheres, nano emulsions, dendrimers, and transdermal systems - have led to significant improvements in how well anti-inflammatory drugs work. With these new delivery systems, the drugs are released in a controlled manner, they are more readily absorbed into the body, they result in fewer side-effects, and they are directed to the area that is inflamed. [104] The unique properties of nanoparticles allow them to get into inflamed tissue more quickly and easily than any other type of dosage form. Additionally, the surface of the nanoparticle can be modified to allow better targeting, longer periods of circulation, and to better interact with the membranes of living cells (e.g., biological tissues). [105,106]

Therapeutic approaches to inflammation have advanced rapidly over the years; however, there remains room for continued innovation within this field with respect to the development of new nanotechnology systems and the incorporation of stimuli-responsive carriers. While manufacturers face challenges (including manufacturing process, stability, cost, and regulatory approvals), continued research is advancing the development and use of new technologies to help treat inflammatory diseases [107]. Furthermore, while inflammation is an important biological defence mechanism of the body, it is also a choreographed physiological response that determines the effectiveness of an individual's ability to heal from tissue damage and/or have a favourable inflammatory response (irrespective of the type of injury sustained). The duration and severity of inflammation can significantly affect the progression and outcome of several acute and chronic conditions. [108,109]

To summarize, advanced pharmaceutical technology is changing how we treat inflammatory diseases and will be important going forward because they will allow us to use safer, more efficient and more user-friendly methods of treatment. [110] Developments in anti-inflammatory treatments are likely to be focused on developing safer biological materials, developing precision medicine and creating smart ways to deliver drugs, which can recognize and respond to specific disease problems in real time. [111,112]

## REFERENCES

1. Harvanová G, Duranková S. Inflammatory process: factors inducing inflammation, forms and manifestations of inflammation, immunological significance of the inflammatory reaction. Alergologia Polska - Polish Journal of Allergology. 2025;12(1):54-61. doi:10.5114/pja.2025.147674.
2. Chen L, Deng H, Cui H, Fang J, Zuo Z, Deng J, et al. Inflammatory responses and inflammation-associated diseases in organs.

Oncotarget. 2018 Jan 23;9(6):7204-18. doi:10.18632/oncotarget.23208. PMID: 29467962; PMCID: PMC5805548.

3. Wallace JL. Mechanisms of protection and healing: current knowledge and future research. The American Journal of Medicine. 2001;110 Suppl 1:S19-23. doi:10.1016/S0002-9343(00)00631-8.
4. Abdulkhaleq LA, Assi MA, Abdullah R, Zamri-Saad M, Taufiq-Yap YH, Hezmee MNM. The crucial roles of inflammatory mediators in inflammation: A review. Veterinary World. 2018 May;11(5):627-35. doi:10.14202/vetworld.2018.627-635. PMID: 29915501; PMCID: PMC5993766.
5. Soares CLR, Wilairatana P, Silva LR, Moreira PS, Barbosa NMMV, da Silva PR, et al. Biochemical aspects of the inflammatory process: A narrative review. Biomedicine & Pharmacotherapy. 2023;168:115764. doi:10.1016/j.biopha.2023.115764.
6. Chopra D, et al. Overview of inflammation. In: Tripathi A, Dwivedi A, Gupta S, Poojan S, editors. *Inflammation Resolution and Chronic Diseases*. Singapore: Springer; 2024. p. 1-18. doi:10.1007/978-981-97-0157-5_1.
7. Ayoub SS. The inflammatory response – an overview. In: Serhan CN, Ward PA, Gilroy DW, editors. Fundamentals of Inflammation. Cambridge: Cambridge University Press; 2010. p. 1-12.
8. Bennett JM, Reeves G, Billman GE, Sturmberg JP. Inflammation–nature's way to efficiently respond to all types of challenges: implications for understanding and managing "the epidemic" of chronic diseases. Frontiers in Medicine. 2018;5:316. doi:10.3389/fmed.2018.00316.
9. Ali KA, Maity A, Roy SD, Pramanik SD, Das PP, Shaharyar MA. Insight into the mechanism of steroidal and non-steroidal anti-inflammatory drugs. In: Kazmi I, Karmakar S, Shaharyar MA, Afzal M, Al-Abbasi FA, editors. How Synthetic Drugs Work. Cambridge (MA): Academic Press; 2023. p. 61-94. doi:10.1016/B978-0-323-99855-0.00004-X.
10. Sinniah A, Yazid S, Flower RJ. From NSAIDs to glucocorticoids and beyond. Cells. 2021;10(12):3524. doi:10.3390/cells10123524.
11. Wen H, Jung H, Li X. Drug delivery approaches in addressing clinical pharmacology-related issues: opportunities and challenges. The AAPS Journal. 2015;17(6):1327-40. doi:10.1208/s12248-015-9814-9.
12. Ezike T, Okpala U, Onoja U, et al. Advances in drug delivery systems, challenges and future directions. Heliyon. 2023;9.
13. Martinho N, Damgé C, Reis CP. Recent advances in drug delivery systems. Journal of Biomaterials and Nanobiotechnology. 2011;2:510-26. doi:10.4236/jbnb.2011.225062.
14. Suri SS, Fenniri H, Singh B. Nanotechnology-based drug delivery systems. Journal of Occupational Medicine and Toxicology. 2007;2:16. doi:10.1186/1745-6673-2-16.
15. Wang J, Wang P, Shao Y, He D. Advancing treatment strategies: a comprehensive review of drug delivery innovations for chronic inflammatory respiratory diseases. Pharmaceutics. 2023;15(8):2151. doi:10.3390/pharmaceutics15082151.
16. Wang H, Zhou Y, Sun Q, Zhou C, Hu S, Lenahan C, et al. Update on nanoparticle-based drug delivery system for anti-inflammatory treatment. Frontiers in Bioengineering and Biotechnology. 2021;9:630352. doi:10.3389/fbioe.2021.630352.
17. Chen L, Deng H, Cui H, Fang J, Zuo Z, Deng J, et al. Inflammatory responses and

inflammation-associated diseases in organs. Oncotarget. 2018;9(6):7204-18. doi:10.18632/oncotarget.23208. PMID: 29467962; PMCID: PMC5805548.
18. Harvanová G, Duranková S. Inflammatory process: factors inducing inflammation, forms and manifestations of inflammation, immunological significance of the inflammatory reaction. Alergologia Polska - Polish Journal of Allergology. 2025;12(1):54-61. doi:10.5114/pja.2025.147674.
19. Harvanová G, Duranková S, Bernasovská J. The role of cytokines and chemokines in the inflammatory response. Alergologia Polska - Polish Journal of Allergology. 2023;10(3):210-219. doi:10.5114/pja.2023.131708.
20. Di Gioacchino M, Della Valle L, Allegra A, Pioggia G, Gangemi S. AllergoOncology: role of immune cells and immune proteins. Clinical and Translational Allergy. 2022;12(4):e12133. doi:10.1002/clt2.12133.
21. Monticielo OA, Mucenic T, Xavier RM, Brenol JCT, Chies JAB. Immune system: Part I. Fundamentals of innate immunity with emphasis on molecular and cellular mechanisms of inflammatory response. Revista Brasileira de Reumatologia. 2010;50(4):434-47. doi:10.1590/S0482-50042010000400008.
22. White M. Mediators of inflammation and the inflammatory process. Journal of Allergy and Clinical Immunology. 1999;103(3 Suppl):S378-81. doi:10.1016/S0091-6749(99)70215-0.
23. Claesson-Welsh L. Vascular permeability—the essentials. Upsala Journal of Medical Sciences. 2015;120(3):135-143. doi:10.3109/03009734.2015.1064501. (tandfonline.com)
24. Nourshargh S, Alon R. Leukocyte migration into inflamed tissues. Immunity. 2014;41(5):694-707. doi:10.1016/j.immuni.2014.10.008.
25. Spiering MJ. Primer on the immune system. Alcohol Research: Current Reviews. 2015;37(2):171-5. doi:10.35946/arcr.v37.2.02. PMID: 26695756; PMCID: PMC4590614.
26. Smith R. Recovery and tissue repair. British Medical Bulletin. 1985;41(3):295-301. doi:10.1093/oxfordjournals.bmb.a072065. (pubmed.ncbi.nlm.nih.gov)
27. Yazdi AS, Ghoreschi K. The interleukin-1 family. In: Ma X, editor. Regulation of Cytokine Gene Expression in Immunity and Diseases. Advances in Experimental Medicine and Biology. Vol 941. Dordrecht: Springer; 2016. p. 21-29. doi:10.1007/978-94-024-0921-5_2.
28. Mihara M, Hashizume M, Yoshida H, Suzuki M, Shiina M. IL-6/IL-6 receptor system and its role in physiological and pathological conditions. Clinical Science. 2012;122(4):143-159. doi:10.1042/CS20110340. (pubmed.ncbi.nlm.nih.gov)
29. Jang DI, Lee AH, Shin HY, Song HR, Park JH, Kang TB, et al. The role of tumor necrosis factor alpha (TNF-α) in autoimmune disease and current TNF-α inhibitors in therapeutics. International Journal of Molecular Sciences. 2021;22(5):2719. doi:10.3390/ijms22052719.
30. Peters M. Actions of cytokines on the immune response and viral interactions: an overview. Hepatology. 1996;23(4):909-16. doi:10.1002/hep.510230436.
31. White MV. The role of histamine in allergic diseases. Journal of Allergy and Clinical Immunology. 1990;86(4 Pt 2):599-605. doi:10.1016/S0091-6749(05)80223-4.
32. Dray A, Perkins M. Bradykinin and inflammatory pain. Trends in Neurosciences.

1993;16(3):99-104. doi:10.1016/0166-2236(93)90121-U.
33. Kuehl FA Jr, Egan RW. Prostaglandins, arachidonic acid, and inflammation. Science. 1980;210(4473):978-84. doi:10.1126/science.6254151.
34. Butola LK, Dhok A, Ambad R, Kanyal D, Jha RK. Leukotrienes and inflammation – a review. Indian Journal of Forensic Medicine & Toxicology. 2021;15(2):295-300.
35. Korhonen R, Lahti A, Kankaanranta H, Moilanen E. Nitric oxide production and signaling in inflammation. Current Drug Targets - Inflammation & Allergy. 2005;4(4):471-479.
36. Jahid M, Khan KU, Rehan-Ul-Haq, Ahmed RS. Overview of rheumatoid arthritis and scientific understanding of the disease. Mediterranean Journal of Rheumatology. 2023;(3).
37. Motta F, Barone E, Sica A, et al. Inflammaging and osteoarthritis. Clinical Reviews in Allergy & Immunology. 2023;64:222-238. doi:10.1007/s12016-022-08941-1.
38. Chen D, Shen J, Zhao W, Wang T, Han L, Hamilton JL, et al. Osteoarthritis: toward a comprehensive understanding of pathological mechanism. Bone Research. 2017;5:16044. doi:10.1038/boneres.2016.44.
39. Rahman M, Yashika, Kaur M, Anurag, Singh O. A review on psoriasis. NeuroQuantology. 2022;20(16):5786-5793. doi:10.48047/NQ.2022.20.16.NQ880588.
40. Wehkamp J, Götz M, Herrlinger K, Steurer W, Stange EF. Inflammatory bowel disease. Deutsches Ärzteblatt International. 2016;113(5):72-82. doi:10.3238/arztebl.2016.0072. PMID: 26900160; PMCID: PMC4782273.
41. Henein MY, Vancheri S, Longo G, Vancheri F. The role of inflammation in cardiovascular disease. International Journal of Molecular Sciences. 2022;23(21):12906. doi:10.3390/ijms232112906.
42. DeFronzo RA, Ferrannini E, Groop L, Henry RR, Herman WH, Holst JJ, et al. Type 2 diabetes mellitus. Nature Reviews Disease Primers. 2015;1:15019. doi:10.1038/nrdp.2015.19.
43. Fakhoury M. Role of immunity and inflammation in the pathophysiology of neurodegenerative diseases. Neurodegenerative Diseases. 2015;15(2):63-69. doi:10.1159/000369933.
44. Nishida A, Andoh A. The role of inflammation in cancer: mechanisms of tumor initiation, progression, and metastasis. Cells. 2025;14(7):488. doi:10.3390/cells14070488.
45. Rao P, Knaus EE. Evolution of nonsteroidal anti-inflammatory drugs (NSAIDs): cyclooxygenase (COX) inhibition and beyond. Journal of Pharmacy & Pharmaceutical Sciences. 2008;11(2):81s-110s. doi:10.18433/J3T886.
46. Gunaydin C, Bilge SS. Effects of nonsteroidal anti-inflammatory drugs at the molecular level. Eurasian Journal of Medicine. 2018;50(2):116-121. doi:10.5152/eurasianjmed.2018.0010. PMID: 30002579; PMCID: PMC6039135.
47. Belvisi MG. Regulation of inflammatory cell function by corticosteroids. Proceedings of the American Thoracic Society. 2004;1(3):207-214. doi:10.1513/pats.200402-002MS.
48. Cain DW, Cidlowski JA. Immune regulation by glucocorticoids. Nature Reviews Immunology. 2017;17:233-247. doi:10.1038/nri.2017.1.
49. Kanatoula DD, Bodner E, Ghoreschi K, Meier K, Solimani F. Non-biologic immunosuppressive drugs for inflammatory and autoimmune skin diseases. Journal der

Deutschen Dermatologischen Gesellschaft. 2024. doi:10.1111/ddg.15270.

50. Hurd ER. Immunosuppressive and antiinflammatory properties of cyclophosphamide, azathioprine and methotrexate. Arthritis & Rheumatism. 1973;16(1):84-90. doi:10.1002/art.1780160114.
51. Zaigham, Hamiduddin, Tauheed A, Ali A. Recent trend in traditional medicine dosage form and present status of Unani and Ayurvedic medicine. International Journal of Pharmaceutical Sciences and Research. 2019;10(4):1640-1649.
52. Kumar L, Verma S, Singh M, Chalotra T, Utreja P. Advanced drug delivery systems for transdermal delivery of non-steroidal anti-inflammatory drugs: a review. Current Drug Delivery. 2018;15(8):1087-1099. doi:10.2174/1567201815666180605114131.
53. Placha D, Jampilek J. Chronic inflammatory diseases, anti-inflammatory agents and their delivery nanosystems. Pharmaceutics. 2021;13(1):64. doi:10.3390/pharmaceutics13010064.
54. Drosopoulou K, Kosheleva RI, Ofrydopoulou A, Tsoupras A, Mitropoulos A. Topical and transdermal delivery of nonsteroidal anti-inflammatory drugs (NSAIDs) for inflammation and pain: current trends and future directions in delivery systems. Processes. 2025;13(3):907. doi:10.3390/pr13030907.
55. Gaballa SA, Saleh MGA, Kompella UB, Alany RG, Abdelkader H. Non-steroidal anti-inflammatory drugs (NSAIDs): ocular pharmacology, pharmaceutical innovations, and drug delivery perspectives. 2026. doi:10.1002/adtp.202500580.
56. Yusuf A, Almotairy ARZ, Henidi H, Alshehri OY, Aldughaim MS. Nanoparticles as drug delivery systems: a review of the implication of nanoparticles' physicochemical properties on responses in biological systems. Polymers. 2023;15(7):1596. doi:10.3390/polym15071596.
57. Yetisgin AA, Cetinel S, Zuvin M, Kosar A, Kutlu O. Therapeutic nanoparticles and their targeted delivery applications. Molecules. 2020;25(9):2193. doi:10.3390/molecules25092193.
58. Nasra S, Bhatia D, Kumar A. Recent advances in nanoparticle-based drug delivery systems for rheumatoid arthritis treatment. 2022;4:3479-3494. doi:10.1039/D2NA00229A.
59. Campos JR, Severino P, Santini A, Silva AM, Shegokar R, Souto SB, et al. Solid lipid nanoparticles (SLN): prediction of toxicity, metabolism, fate and physicochemical properties. In: Shegokar R, editor. Nanopharmaceuticals. Amsterdam: Elsevier; 2020. p. 1-15. doi:10.1016/B978-0-12-817778-5.00001-4.
60. Lim SJ, Kim CK. Formulation parameters determining the physicochemical characteristics of solid lipid nanoparticles loaded with all-trans retinoic acid. International Journal of Pharmaceutics. 2002;243(1-2):135-146. doi:10.1016/S0378-5173(02)00269-7.
61. Paliwal R, Paliwal SR, Kenwat R, Kurmi BD, Sahu MK. Solid lipid nanoparticles: a review on recent perspectives and patents. Expert Opinion on Therapeutic Patents. 2020;30(3):179-194. doi:10.1080/13543776.2020.1720649.
62. Torchilin VP. Recent advances with liposomes as pharmaceutical carriers. Nature Reviews Drug Discovery. 2005;4:145-160. doi:10.1038/nrd1632.
63. Bozzuto G, Molinari A. Liposomes as nanomedical devices. International Journal of

Nanomedicine. 2015;10:975-999. doi:10.2147/IJN.S68861.
64. Vishvakrama P, Sharma S. Liposomes: an overview. International Journal of Research in Pharmaceutical and Biomedical Sciences. Review article.
65. Ahmed KS, Hussein SA, Ali AH, Korma SA, Lipeng Q, Jinghua C. Liposome: composition, characterisation, preparation, and recent innovation in clinical applications. Journal of Drug Targeting. 2019;27(7):742-761. doi:10.1080/1061186X.2018.1527337.
66. van Alem CMA, Metselaar JM, van Kooten C, Rotmans JI. Recent advances in liposomal-based anti-inflammatory therapy. Pharmaceutics. 2021;13(7):1004. doi:10.3390/pharmaceutics13071004.
67. Rahman M, Kumar V, Beg S, Sharma G, Katare OP, Anwar F. Emergence of liposome as targeted magic bullet for inflammatory disorders: current state of the art. Artificial Cells, Nanomedicine, and Biotechnology. 2016;44(7):1597-1608. doi:10.3109/21691401.2015.1129617.
68. Varde NK, Pack DW. Microspheres for controlled release drug delivery. Expert Opinion on Biological Therapy. 2004;4(1):35-51. doi:10.1517/14712598.4.1.35.
69. Freiberg S, Zhu XX. Polymer microspheres for controlled drug release. International Journal of Pharmaceutics. 2004;282(1-2):1-18. doi:10.1016/j.ijpharm.2004.04.013.
70. Jacob S, Nair AB, Shah J, Sreeharsha N, Gupta S, Shinu P. Emerging role of hydrogels in drug delivery systems, tissue engineering and wound management. Pharmaceutics. 2021;13(3):357. doi:10.3390/pharmaceutics13030357.
71. Gupta A, Lee J, Ghosh T, Nguyen VQ, Dey A, Yoon B, et al. Polymeric hydrogels for controlled drug delivery to treat arthritis. Pharmaceutics. 2022;14(3):540. doi:10.3390/pharmaceutics14030540.
72. Chelu M, Popa M, Calderón Moreno JM. Applications of hydrogels in emergency therapy. Gels. 2025;11(4):234. doi:10.3390/gels11040234.
73. Sadraei A, Naghib SM, Rabiee N. 4D printing chemical stimuli-responsive hydrogels for tissue engineering and localized drug delivery applications – part 2. Expert Opinion on Drug Delivery. 2025;22(4):491-510. doi:10.1080/17425247.2025.2466768.
74. Trucillo P. Biomaterials for drug delivery and human applications. Materials. 2024;17(2):456. doi:10.3390/ma17020456.
75. Peters JT, Wechsler ME, Peppas NA. Advanced biomedical hydrogels: molecular architecture and its impact on medical applications. Regenerative Biomaterials. 2021;8(6):rbab060. doi:10.1093/rb/rbab060.
76. Park J, Yu D, Kim T, Choi C, Yuk SA, Kim H. Hydrogel-integrated nanotheranostic platforms for localized diagnosis and therapy. Journal of Nanotheranostics. 2026;7(2):10. doi:10.3390/jnt7020010.
77. Qadir A, Faiyazuddin MD, Hussain MDT, Alshammari TM, Shakeel F. Critical steps and energetics involved in a successful development of a stable nanoemulsion. Journal of Molecular Liquids. 2016;214:7-18. doi:10.1016/j.molliq.2015.11.050.
78. Kathe K, Kathpalia H. Film forming systems for topical and transdermal drug delivery. Asian Journal of Pharmaceutical Sciences. 2017;12(6):487-497. doi:10.1016/j.ajps.2017.07.004.
79. Cook AB, Perrier S. Branched and dendritic polymer architectures: functional nanomaterials for therapeutic delivery. 2019;29(28):1901001. doi:10.1002/adfm.201901001.

80. Ulbrich W, Lamprecht A. Targeted drug-delivery approaches by nanoparticulate carriers in the therapy of inflammatory diseases. Journal of the Royal Society Interface. 2010;7(Suppl 1):S55-S66. doi:10.1098/rsif.2009.0285.focus.
81. Tu Z, Zhong Y, Hu H, Shao D, Haag R, Schirner M, et al. Design of therapeutic biomaterials to control inflammation. Nature Reviews Materials. 2022;7:557-574. doi:10.1038/s41578-022-00427-1.
82. Huang Y, Guo X, Wu Y, Chen X, Feng L, Xie N, et al. Nanotechnology's frontier in combatting infectious and inflammatory diseases: prevention and treatment. Signal Transduction and Targeted Therapy. 2024;9:34. doi:10.1038/s41392-024-01743-7.
83. Liu J, Liu Z, Pang Y, Zhou H. The interaction between nanoparticles and immune system: application in the treatment of inflammatory diseases. Journal of Nanobiotechnology. 2022;20:127. doi:10.1186/s12951-022-01349-0.
84. Perrigue PM, Murray RA, Mielcarek A, Henschke A, Moya SE. Degradation of drug delivery nanocarriers and payload release: a review of physical methods for tracing nanocarrier biological fate. Pharmaceutics. 2021;13(6):770. doi:10.3390/pharmaceutics13060770.
85. Abdelkawi A, Slim A, Zinoune Z, Pathak Y. Surface modification of metallic nanoparticles for targeting drugs. Coatings. 2023;13(9):1660. doi:10.3390/coatings13091660.
86. Deng X, Zhang Z, Ren T, et al. Regulation of oxidative stress and inflammation caused by drug accumulation in the TME based on EPR-passive strategy and active targeting. Cancer Nanotechnology. 2025;16:40. doi:10.1186/s12645-025-00342-1.
87. Moritz M, Geszke-Moritz M. Mesoporous materials as elements of modern drug delivery systems for anti-inflammatory agents: a review of recent achievements. Pharmaceutics. 2022;14(8):1542. doi:10.3390/pharmaceutics14081542.
88. Yu H, Gao R, Liu Y, Fu L, Zhou J, Li L. Stimulus-responsive hydrogels as drug delivery systems for inflammation targeted therapy. Advanced Science. 2024;11(2):2306152. doi:10.1002/advs.202306152.
89. Anselmo AC, Mitragotri S. An overview of clinical and commercial impact of drug delivery systems. Journal of Controlled Release. 2014;190:15-28. doi:10.1016/j.jconrel.2014.03.053.
90. Fenton OS, Olafson KN, Pillai PS, Mitchell MJ, Langer R. Advances in biomaterials for drug delivery. Advanced Materials. 2018;30(29):1705328. doi:10.1002/adma.201705328.
91. Manzari MT, Shamay Y, Kiguchi H, Rosen N, Scaltriti M, Heller DA. Targeted drug delivery strategies for precision medicines. Nature Reviews Materials. 2021;6:351-370. doi:10.1038/s41578-021-00269-6.
92. Reddy KTK, Reddy AS. Recent breakthroughs in drug delivery systems for targeted cancer therapy: an overview. Cellular, Molecular and Biomedical Reports. 2025;5(1):13-27. doi:10.55705/cmbr.2025.456494.1246.
93. Zhao Z, Ukidve A, Kim J, Mitragotri S. Targeting strategies for tissue-specific drug delivery. Cell. 2020;181(1):151-167. doi:10.1016/j.cell.2020.02.001.
94. Singh AP, Biswas A, Shukla A, Maiti P. Targeted therapy in chronic diseases using nanomaterial-based drug delivery vehicles. Signal Transduction and Targeted Therapy. 2019;4:33. doi:10.1038/s41392-019-0068-3.

95. Srinivasarao M, Low PS. Ligand-targeted drug delivery. Chemical Reviews. 2017;117(19):12133-12164. doi:10.1021/acs.chemrev.7b00013.
96. Deng Z, Liu S. Inflammation-responsive delivery systems for the treatment of chronic inflammatory diseases. Drug Delivery and Translational Research. 2021;11:1475-1497. doi:10.1007/s13346-021-00977-8.
97. Haley RM, von Recum HA. Localized and targeted delivery of NSAIDs for treatment of inflammation: a review. Experimental Biology and Medicine. 2019;244(6):433-444. doi:10.1177/1535370218787770.
98. Yasmin F, Najeeb H, Shaikh S, Hasanain M, Naeem U, Moeed A, et al. Novel drug delivery systems for inflammatory bowel disease. World Journal of Gastroenterology. 2022;28(18):1922-1933. doi:10.3748/wjg.v28.i18.1922. PMID: 35664964; PMCID: PMC9150062.
99. Hussain Z, Thu HE, Amjad MW, Hussain F, Ahmed TA, Khan S. Exploring recent developments to improve antioxidant, anti-inflammatory and antimicrobial efficacy of curcumin: a review of new trends and future perspectives. Materials Science and Engineering: C. 2017;77:1316-1326. doi:10.1016/j.msec.2017.03.226.
100. Qin Q, Wang M, Zou Y, Yang D, Deng Y, Lin S, et al. Development of nanoparticle-based drug delivery system for inflammation treatment and diagnosis. MedComm – Biomaterials and Applications. 2023. doi:10.1002/mba2.65.
101. Furman D, Campisi J, Verdin E, Carrera-Bastos P, Targ S, Franceschi C, et al. Chronic inflammation in the etiology of disease across the life span. Nature Medicine. 2019;25:1822-1832. doi:10.1038/s41591-019-0675-0.
102. Ptaschinski C, Lukacs NW. Acute and chronic inflammation induces disease pathogenesis. In: Coleman WB, Tsongalis GJ, editors. Molecular Pathology. 2nd ed. Amsterdam: Academic Press; 2018. p. 25-43. doi:10.1016/B978-0-12-802761-5.00002-X.
103. Libby P, Smith R, Rubin EJ, Glassberg MK, Farkouh ME, Rosenson RS. Inflammation unites diverse acute and chronic diseases. European Journal of Clinical Investigation. 2024. doi:10.1111/eci.14280.
104. Chavda VP, Feehan J, Apostolopoulos V. Inflammation: the cause of all diseases. Cells. 2024;13(22):1906. doi:10.3390/cells13221906.
105. Rajendran P, Chen YF, Chen YF, Chung LC, Tamilselvi S, Shen CY, et al. The multifaceted link between inflammation and human diseases. Journal of Cellular Physiology. 2018;233(9):6458-6471. doi:10.1002/jcp.26479.
106. Parvin N, Joo SW, Mandal TK. Biodegradable and stimuli-responsive nanomaterials for targeted drug delivery in autoimmune diseases. Journal of Functional Biomaterials. 2025;16(1):24. doi:10.3390/jfb16010024.
107. Gao L, Wang J, Bi Y. Nanotechnology for neurodegenerative diseases: recent progress in brain-targeted delivery, stimuli-responsive platforms, and organelle-specific therapeutics. International Journal of Nanomedicine. 2025;20:11015-11044. doi:10.2147/IJN.S549893.
108. Taneja A, Panda HS, Panda JJ, Singh TG, Kour A. Revolutionizing precision medicine: unveiling smart stimuli-responsive nanomedicine. Advanced Therapeutics. 2025. doi:10.1002/adtp.202500073.
109. Majumder J, Minko T. Multifunctional and stimuli-responsive nanocarriers for targeted therapeutic delivery. Expert Opinion on Drug Delivery. 2021;18(2):205-227. doi:10.1080/17425247.2021.1828339.

110. Wu Y, Wang P, Wu S, Xu H, Yang W, Tu Y, et al. Bridging pharmacology and nanotechnology: mechanistic insights into traditional Chinese medicine-based nanodelivery systems for rheumatoid arthritis. International Journal of Nanomedicine. 2026;21. doi:10.2147/IJN.S574688.
111. Mohamed RGA, Ali SM, Ahmed IS, Rawas-Qalaji M, Hussain Z. Next-generation nanocarriers for colorectal cancer: passive, active, and stimuli-responsive strategies for precision therapy. Nanoscale. 2025. doi:10.1039/D5NR03654A.
112. Croitoru GA, Niculescu AG, Epistatu D, Mihaiescu DE, Antohi AM, Grumezescu AM, et al. Nanostructured drug delivery systems in immunotherapy: an updated overview of nanotechnology-based therapeutic innovations. Applied Sciences. 2024;14(19):8948. doi:10.3390/app14198948.

HOW TO CITE: Atul Pratap, Saniyasnain , Preeti Kuniyal, Advanced Drug Delivery Strategies for Targeted Anti-inflammatory Therapy, Int. J. of Pharm. Sci., 2026, Vol 4, Issue 9, 2918-2936, https://doi.org/10.5281/zenodo.22915842