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Self-Destructive Nanoparticles of Drug Delivery

M Sangeetha*; U Siri; G Venkat Sai Kumar; M Gajendar; T Rama Rao

Department of Pharmaceutical Chemistry, CMR College of Pharmacy, Kandlakoya (V), Medchal, Hyderabad-501401, Telangana, India.

***Corresponding Author(s): M Sangeetha**

Department of Pharmaceutical Chemistry, CMR College of Pharmacy, Kandlakoya (V), Medchal, Hyderabad-501401, Telangana, India.

Tel: +918919886900;

Email: sangeetha.kodiganti@gmail.com

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Abstract

This review is provided a detailed information about the introduction, mechanisms of self- destructive nanoparticles, benefits of nanoparticles, future perspectives and different types of applications of self-destructive nanoparticles. Nanoparticles are tiny materials having size ranges from 1 to 100 nm. They can be classified into different classes based on their properties, shapes or sizes. Nanoparticles possess unique physical and chemical properties due to their high surface area and nanoscale size. Their optical properties are reported to be dependent on the size, which imparts different colours due to absorption in the visible region. Their reactivity, toughness and other properties are also dependent on their unique size, shape and structure. Due to these characteristics, they are suitable candidates for various commercial and domestic applications, which include catalysis, imaging, medical applications, energy-based research, and environmental applications. However, nanoparticles also bring with them unique environmental and societal challenges, particularly in regard to toxicity.

Introduction

Over the past two decades, nanotechnology has utterly revolutionized how medicine is delivered by providing new tools to improve localization and accuracy for therapeutic applications. In particular, self-destructing nanoparticles represent a clever twist around controlled release systems and targeted medicine delivery. The current tools suffer from various limitations that include non-specific distribution, rapid clearance from the body and systemic toxicity. For the treatment of challenging diseases such as cancer, for example with limited therapeutic windows or a high likelihood that off-target effects could result in substantial side-effects these adverse outcomes become worrisome [1,2]. Self-eliminating nanoparticles address these issues by enabling drugs to be delivered precisely where they are needed while providing triggerable functions that enhance therapeutic efficacy and limit collateral damage. Despite its simplicity, self-destructing nanoparticles have an exceptional kill rate. These nanoparticles are engineered to degrade or unbind by encountering particular biological, (degradable) or environmental stimuli. These are triggered by physiological cues such as pH, temperature, redox potential or enzyme activity that can differ markedly between healthy and diseased tissues [3-5]. This response is necessary to protect the therapeutic cargo from releasing or being degraded in circulation, thus maintaining the stability of nanoparticles during systemic travel. Preceded with passing step of addressing that followed by the ability to communicate, targeted drug delivery systems are designed so they transport nanoparticles intact only before reaching specific tissue where acidity, or enzyme expression differences from normal tissues and then start degradation [6-8].

For example, tumours in cancer therapy often contain an acidic environment and abnormally high levels of specific enzymes (Matrix Metallo Proteinases [MMPs]) Nanoparticles that

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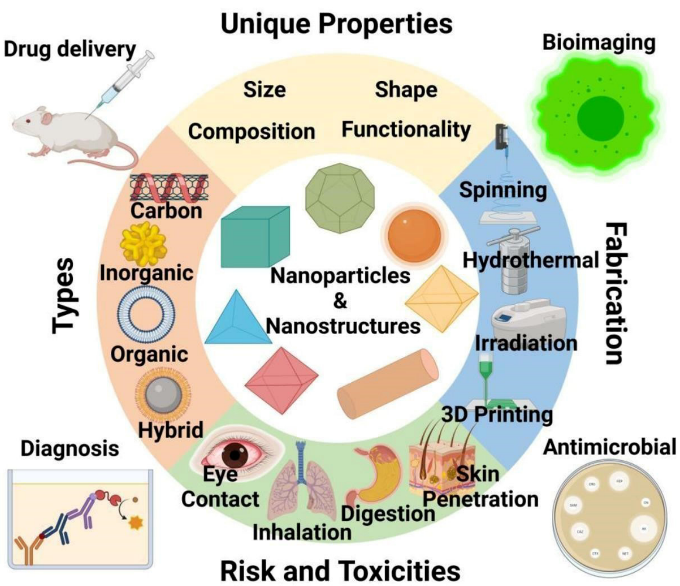
respond to these stimuli by disintegrating can be designed so they will only release into the tumour, thereby minimizing systemic toxicity and improving therapeutic outcomes for patients [9-10]. In addition, redox-sensitive nanoparticles take advantage of the presence of high levels of Reactive Oxygen Species (ROS) in cancer cells, promoting breakdown and drug release from these polymeric carriers under [11] or inside [12] oxidizing environments. By creating such nanoparticles, you not only enhance precision in drug delivery but also a new era of personalized & adaptive therapeutic strategies wherein treatments can be customised based on the unique biochemistry of each patient. Beyond cancer, self-destructing nanoparticles have great potential for many other uses including inflammatory disorders, infectious diseases, and cardiovascular ailments. From small Molecule to Pharmaceutical biological including proteins, peptides, and nucleic acids [13-15], their adaptability makes them perfect for delivering a great range of therapeutic agents. Moreover, self-destructive nanocarriers are being investigation for *thoracoscopic* uses, in which case they may integrate diagnostic and therapeutic purposes into one platform. This provides a dynamic and complete method of therapy as it allows real-time monitoring of medication release and illness development [16,17].



Including *biodegradable* components guarantee that, after their delivery of their payload, self-destructing nanoparticles safely breakdown and are cleared from the body. This lowers the possibility of long-term toxicity or accumulation in tissues, therefore addressing a possible problem with non-biodegradable nanoparticles [18,19]. Commonly employed materials in the building of these nanoparticles include poly (lactic-co-glycolic acid) (PLGA), Polyethylene Glycol (PEG), and other biopolymers, therefore providing biocompatibility and adjustable degradation profiles fit for particular therapeutic demands [20-22].

All things considered, self-destructing nanoparticles mark a major breakthrough in drug delivery technologies as they allow highly focused, regulated, safe therapeutic systems. By utilizing the particular properties of sick tissues and combining biodegradable elements, these nanoparticles provide a potent platform for boosting therapy effectiveness while reducing adverse effects. As research continues, the future of self-destructing nanoparticles has immense promise, not just in cancer treatment but also across a broad spectrum of medicinal uses.

Mechanism of action

Self-destructing nanoparticles are created to disintegrate or deconstruct in reaction to particular physiological processes, enabling precise medicine delivery. The degradation may be produced by several sources, including pH fluctuations, enzymatic activity, oxidative stress, or temperature shifts. These triggers provide controlled release of drugs at the target area, reducing harm to healthy tissues.

pH-responsive degradation

Many malignancies and inflammatory tissues have an acidic microenvironment. pH-responsive nanoparticles are created to disintegrate when exposed to the reduced pH in these areas. Materials such as poly (lactic-co-glycolic acid) (PLGA) and poly (β-amino esters) degrade quickly under acidic circumstances, releasing their therapeutic payloads specifically in the targeted location [1,2]. For example, pH-sensitive nanocarriers breakdown in acidic tumour microenvironments, triggering the release of encapsulated medications directly into cancer cells [3,4].

Enzyme-triggered disassembly

Enzymes that are over expressed in particular illnesses may function as effective triggers for nanoparticles disintegration. For instance, Matrix Metallo Proteinases (MMPs), which are frequent in tumours, may shatter peptide bonds within nanoparticles, leading to the release of their contents. This enzymatic breakdown allows the Nanoparticles to respond selectively to diseased cells while keeping stable in healthy surrounds [5,6].

Redox-Responsive Mechanisms

Oxidative stress, characterized by high levels of Reactive Oxygen Species (ROS), is a feature of many disorders, including cancer and cardiovascular difficulties. Redox-responsive nanoparticles are engineered to disintegrate in the presence of high ROS levels, releasing their therapeutic contents selectively in the sick areas. These nanoparticles often have disulfide connections that are disrupted in a reducing environment, leading to disintegration and drug release [7,8].

Thermo-responsive disassembly

Temperature-sensitive nanoparticles are designed to degrade or modify their structural form in response to temperature differences. This is notably useful in hyperthermia therapy, where localized heating of tumour tissues may promote the release of medications from the nanoparticles. Thermo-responsive materials such as poly (N-isopropyl acrylamide) (PNIPAM) are widely employed to produce nanoparticles that respond to changes in temperature [9,10].

Benefits

Self-destructing nanoparticles give considerable benefits in targeted drug administration, giving increased therapeutic accuracy and decreased adverse effects. Some of the primary advantages include:

Targeted and controlled drug release

Self-destructing nanoparticles are intended to release their therapeutic payload in response to certain biological stimuli like pH, enzymes, or redox conditions, guaranteeing the medicine is delivered exactly at the place of interest. This precision targeting considerably lowers off-target effects and boosts the efficiency of therapy, notably in cancer where surrounding healthy tissues are commonly destroyed by traditional medicines [1-3].

Minimized toxicity and side effects

These nanoparticles may release medications in a regulated way at the illness site, decreasing systemic exposure and minimizing adverse effects. For example, pH-responsive nanoparticles might release chemotherapeutic medicines in the acidic environment of a tumour, sparing healthy tissues and lowering toxicity [4,6].

Biodegradability and Reduced Accumulation

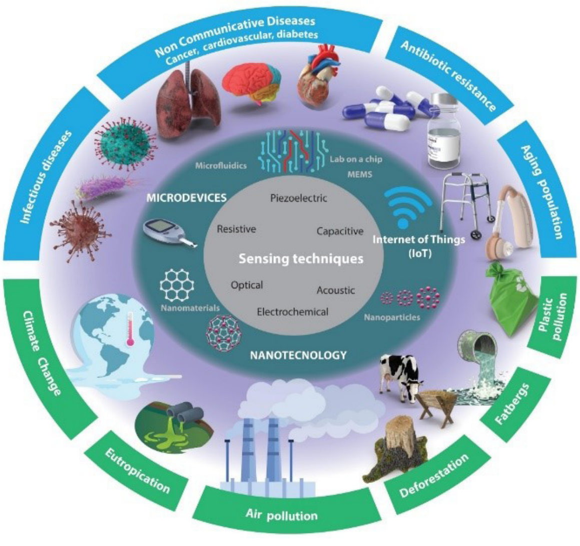
Nanoparticles are commonly produced from biodegradable materials like PLGA, which break down into non-toxic metabolites that the body can reject naturally. This helps avoid long-term build-up in organs such as the liver or kidneys, which is a typical concern with non-biodegradable nanoparticles [7,8].

Enhanced Patient Compliance

By managing the release of therapeutic substances, self-destructing nanoparticles may lower the frequency of medication delivery. This is especially important for patients with chronic conditions, because frequent dosage may lead to poor patient compliance. Sustained medication release from these nanoparticles promotes convenience and quality of life for patients [5,9].

Stimuli-Responsive Precision

These nanoparticles are activated by certain physiological situations such pH shifts, enzyme over expression, or redox environments observed in sick tissues. This guarantees that the medicine is delivered just where and when it is required, boosting therapeutic accuracy [10,11].



Multifunctionality and co-delivery of therapeutics

Self-destructing nanoparticles may be created to deliver numerous medications concurrently or to mix therapeutic and diagnostic substances (theragnostic). This multifunctionality is especially helpful for individualized medicine and enables for more complete treatment options [12,13].

Improved bioavailability

Nanoparticles may boost the bioavailability of poorly soluble medicines, enhancing their therapeutic effectiveness. Encapsulating these medications in nanoparticles provides greater absorption and larger concentrations at the target location, increasing therapeutic results [14,15].

Future perspectives

However, there are also several challenges and potential future directions for developing and using nanoparticles. One major challenge is synthesizing and processing nanoparticles with precise size and shape control [23]. Many methods for synthesizing nanoparticles involve high temperatures and harsh chemical conditions, which can be challenging to scale up for large-scale production. In addition, the size and shape of the nanoparticles can significantly impact their properties and potential applications, so it is essential to synthesize nanoparticles with precise size and shape control. Another challenge is the environmental impact of nanoparticles.

In terms of future directions, one promising area is the use of different types of nanoparticles for energy storage, conversion, and protection of the environment. For example, metal nanoparticles could be used to improve batteries' performance or develop more efficient solar cells [23]. There is also ongoing research on nanoparticles in medicine, including drug delivery and cancer therapy.

Currently, huge numbers of theoretical and experimental literature studies of nanomaterials and nanotechnology have been witnessed. Future technologies depend upon how effectively materials can be manipulated on the nanoscale for various applications. However, at the same time, the development and effective utilization of nanomaterials involve many challenges. Some of the critical challenges are mentioned below:

(a) The presence of defects in nanomaterials can affect their performance and their inherent characteristics can be compromised. For instance, carbon nanotubes are one of the strongest materials that are known. However, impurities, discontinuous tube lengths, defects, and random orientations can substantially impair the tensile strength of carbon nanotubes.

(b) Nanomaterials utilization in industry is being increased, and there is also demand for nanoscale material production at higher rates. The extent to which nanoparticles-based materials can contribute to cellular toxicity is unclear. A proper and systematic understanding of the interaction of nanomaterials with cells, tissues, and proteins is critical for the safe design and commercialization of nanotechnology.

The future of advanced technology is linked with advancements in the field of nanotechnology. The dream of clean energy production is becoming possible with the advancement of nanomaterials-based engineering strategies. These materials have shown promising results, leading to new generations of hydrogen fuel cells and solar cells, acting as efficient catalysts for water splitting, and showing excellent capacity for hydrogen storage. Nanomaterials have a great future in the field of nanomedicine. Nanocarriers can be used for the delivery of therapeutic molecules.

Although nanoparticles and nano-drug delivery systems are widely understood, their actual impact on the healthcare system- including in the treatment and diagnosis of cancer-remains quite restricted. In the end, the use of nanoparticles will develop along with our growing understanding of diseases at the cellular scale or that reflect a nanomaterials- sub cellular scale equivalent biomarker identification to open up new pathways for diagnosis and treatment.

The creation of nanorobots and nanodevices that work in tissue diagnostic and repair mechanisms with full external methods of control has generated a significant amount of attention. But just as with their advantages, nanomedicine's possible drawbacks must also be thoroughly investigated, both for humans and the ecosystem as a whole. Therefore, a thorough examination of the potential acute or long- term harmful consequences of novel nanomaterials on people and the environment is necessary. The accessibility of nanomedicine's would be another topic of study that requires more study input as they become more and more Widespread.

Research is ongoing to optimize the design and functionality of these nanoparticles, addressing challenges like stability, biocompatibility, and production scalability. As the technology advances, it holds the potential for significant impacts across multiple industries.

Toxicities in self-destructive nanoparticles

Beside many industrial and medical applications, there are certain toxicities which are associated with nanoparticles and other nanomaterials and basic knowledge is required for these toxic effects to encounter them properly. However, the application of Nanoparticles for environmental treatment deliberately injects or dumps engineered. The advantages of magnetic nanoparticles such as their small size, high reactivity and great capacity, could become potential lethal factors by inducing adverse cellular toxic and harmful effects, unusual in micron-sized counter parts. Although some studies have also addressed the toxicological effects of nanoparticles on animal cells and plant cells the toxicological studies with magnetic nanoparticles on plants to date are still limited [24].

The respiratory system represents a unique target for the potential toxicity of nano particles due to the fact that in addition to being the portal of entry for inhaled particles, it also receives the entire cardiac output [24].

Due to this binding, some particles generate adverse biological outcomes through protein unfolding, fibrillation, thiol cross linking, and loss of enzymatic activity. Another paradigm is the release of toxic ions when the thermodynamic properties of materials favour particles dissolution in a suspending medium or biological environment.

Nanoparticles tend to aggregate in hard water and seawater and are greatly influenced by the specific type of organic matter or other natural particles (colloids) present in fresh water. The state of dispersion will alter the ecotoxicity, but many a biotic factors that influence this, such as pH, salinity, and the presence of organic matters remain to be systematically investigated as part of eco toxicological studies [23,24].

Toxicity of polymeric and liposomal nanoparticles

This category of nanoparticles is probably the least problematic with respect to toxicity because the particles are very often typically either made from or covered with natural or highly biocompatible polymers (such as PEG). In drug delivery applications, these particles often carry drugs that are cytotoxic by design (to kill cancer cells) but they are prevented from attacking other regions of the body by the selective targeting described earlier in this review.

The incorporation of natural polymers such as chitosan or natural lipids in the assembly of polymer- or liposome-based nanoparticles is beneficial because these polymers are not recognized as being foreign by the body and are readily metabolized nanoparticles made from synthetic polymers can vary widely in the rate of clearance from the blood stream and accumulation in Mononuclear Phagocytic System (MPS) organs (MPS) organs (such as the liver and spleen) depending on polymer type and composition. The incorporation of PEG in the nanoparticle structure can delay the removal of nanoparticles from the blood stream, as discussed earlier. PEG-coated particles are therefore considered to be less toxic than uncoated particles because they are less likely to saturate the mononuclear phagocytic system.

Toxic effects of nanoparticles on health

With the discovery of CNTs, studies on the toxicity of nano particles to human health began in the 2000s. Since then, researchers have conducted studies to assess the potential adverse effects of nanoparticles exposure on various organs, including the lungs, liver, kidneys, and brain. Studies have shown that nanoparticles can enter the human body through inhalation, ingestion, and skin contact, causing damage to cells, tissues, and organs.

Recent studies have focused on understanding the mechanisms of nanoparticles toxicity and identifying factors that contribute to their adverse effects. One of the main findings is that the size, shape, surface area, and chemical composition of nanoparticles are key determinants of their toxicity. In addition, the interactions of nanoparticles with biological systems such as proteins, enzymes, and DNA can affect their toxicity. The next step in nanoparticles toxicity research is to develop strategies to mitigate the risks associated with nanoparticles exposure.

This includes developing safe and efficient methods for nanoparticles synthesis, identifying biomarkers of nanoparticles toxicity, and developing protective measures for workers in industries that use nanoparticles. In addition, more research is needed to understand the long-term effects of nanoparticles exposure on human health and the environment. In conclusion, nanoparticles are a double-edged sword, as they have the potential to revolutionize fields, but at the same time, they pose significant health risks. Therefore, it is critical to continue to study the toxic effects of nanoparticles on human health and to develop strategies to mitigate these risks.

This part discusses the influence of nanoparticles exposure on the respiratory system, nervous system, endocrine system, immune system, and reproductive system, as well as the relationship with the occurrence and development of tumours. A multifaceted review of the effects of nanoparticles exposure on human health has been conducted.

Applications

Some of the important applications are given below by considering the unique properties of the nanoparticles:

Applications in drugs and medications

Nano-sized inorganic particles of either simple or complex nature, display unique, physical and chemical properties and represent an increasingly important material in the development of novel nanodevices which can be used in numerous physical, biological, biomedical and pharmaceutical applications.

Iron oxide particles such as magnetite (Fe3O4) or its oxidized form maghemite (Fe2O3) are the most commonly employed for biomedical applications.

Super paramagnetic iron oxide nanoparticles with appropriate surface chemistry can be used for numerous in vivo applications such as MRI contrast enhancement, tissue repair, and immunoassay, detoxification of biological fluids hyperthermia, drugs delivery and cell separation.

All of these biomedical applications require that the nanoparticles have high magnetization value, a size smaller than 100 nm and a narrow particle size distribution.

Various polymers have been used in drug delivery research as they can effectively deliver the drugs to the target site thus increases the therapeutic benefit, while minimizing side effects.

Targeted drug delivery is also an important potential application of nanoparticles. ZnO and nanoparticles were efficiently used for targeted drug delivery and selective destruction of tumour cells. Moreover, nanoparticles have been successfully used in different medical applications such as cellular imaging, or in biosensors for DNA, carbohydrates, proteins, and heavy metal ions determination of blood glucose levels, and for medical diagnostics to detect bacteria and viruses [25].

Applications in manufacturing and materials

Among the nanotechnology consumer products to date, health fitness products from the largest category, followed by the electronic and computer category as well as home and garden category. Nanotechnology has been touted as the next revolution in many industries including food processing and packing [25]. The resonance wavelength strong depends on size and shape of nanoparticles the inter particle distance, and the dielectric property of the surrounding medium.

Applications in the environment: The increasing area of engineered nanoparticles in industrial and household applications leads to the release of such materials into the environment [24,25].

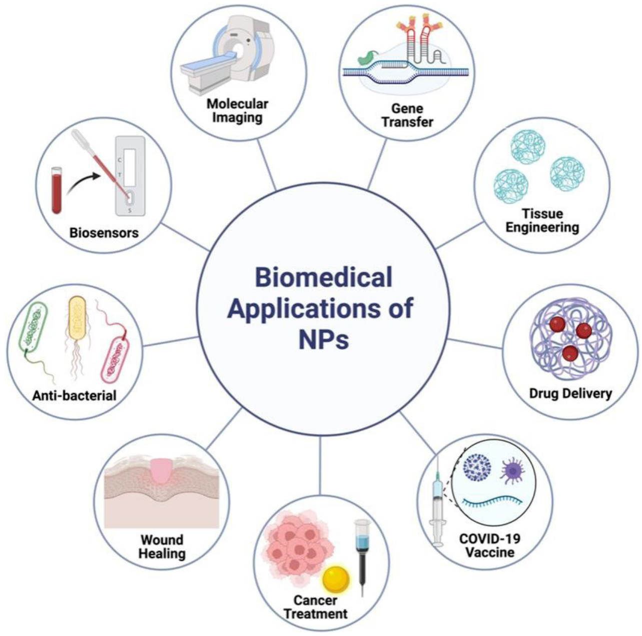
The interaction of contaminants with nanoparticles is dependent on the nanoparticles characteristics, such as size, composition, morphology, porosity, aggregation/disaggregation and aggregate structure.

The removal of heavy metals such as mercury, lead, thallium, cadmium and arsenic from natural water has attracted considerable attention because of their adverse effects on environmental and human health. Super paramagnetic iron oxide nanoparticles are an effective sorbent material for this toxic soft material. Due to their tiny size and distinctive physical and chemical characteristics, nanoparticles appeal to various environmental applications. The properties of nanoparticles and their advantages are illustrated. The following are some possible nanoparticles uses in the environment.

Conclusion

Among the numerous limitations of current drug delivery methods are non-specific distribution, quick clearance from the body, and systemic toxicity. These nanoparticles are engineered to break down or disassemble in response to particular biological or environmental stimuli. The versatility of these nanoparticles makes them great for delivering a wide array of therapeutic agents, from small-molecule medications to biologics such as proteins, peptides, and nucleic acids.

Here we have discussed many of the mechanisms like pH, patient compliance, biodegradability, bioavailability, minimized



toxicities and side effects.

Due to their tiny size, nanoparticles have large surface area, which make them suitable candidate for various applications [24]. Beside this, the optical properties are also dominant at that size, which further increase the importance of these materials in photo catalytic applications. Synthetic techniques can be useful to control the specific morphology, size and magnetic properties of nanoparticles. Though nanoparticles are useful for many applications, but still there are some health hazard concerns due to their uncontrollable use and discharge to natural environment, which should be consider for make the use of nanoparticles more convenient and environment friendly.

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