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Nanotechnology, and its versatile applications in medicine, environment, energy, textiles, food industry

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Abstract

Nanotechnology refers to technology that is applied at the nanoscale and has global applications. The unique physical and chemical properties of materials used in nanotechnology are exploited for innovative applications that benefit society. This study provides a comprehensive overview of the versatile and innovative applications of nanotechnology in various fields such as medicine, environment, energy, textiles, and food. To contribute to the literature, recent developments, and applications in these fields are reviewed in detail. This article highlights the applications of nanotechnology in critical areas such as vaccine development, tissue engineering, drug delivery systems, surgical applications, orthopedic implants, and nerve tubulation in medicine. In environmental applications, solutions such as sustainable agriculture, carbon footprint reduction, smart sensors, and biodegradable materials come to the fore. In the energy sector, the importance of nanomaterials in the capture, storage, and functional use of energy is discussed. In addition, nanomaterials used in the textile industry provide fabrics with properties such as water repellency, antibacterial, antistatic, self-cleaning, and wrinkle resistance, while in the food industry nanomaterials add value to the industry by providing active, smart, enhanced, and bio-based packaging solutions.

This review aims to guide researchers working in this field by analyzing the current state, and potential of nanotechnology in detail. The potential of nanotechnology to shape a sustainable future and provide innovative solutions in various sectors is emphasized.

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1. Introduction

Nanotechnology is a frequently heard application today. Although little is known about it, many definitions are put forward in this field of technology [1]. In its simplest definition, nanotechnology is known as the technology that operates at the nanoscale. Following this first definition, various interpretations are put forward. This primary definition requires a more comprehensive explanation of the elements that define the nanoscale, and their details. Therefore, nanotechnology emphasizes a research field that includes structures, devices, and systems with atoms on the scale of 1-100 nm with new properties [2]. Nanotechnology includes systems, and materials that represent chemical, physical, and biological properties that have been significantly improved due to their nanoscale size. Colloidal science, chemistry, physics, biology, and other scientific disciplines are known as a subclassification of this technology, and enable the investigation of these nanoscale phenomena [3]. Nanostructured materials are seeing significant advances, and innovations every day, pushing the potential of the realizable [4]. The world of science, which is constantly developing day by day, contributes to living organisms in many fields with the development of nanotechnology [5]. Accordingly, nanotechnology is effectively applied in multiple fields today [6]. Materials brought to nano size by so-called top or bottom methods exhibit unique physical, chemical, and mechanical properties, and high performance. Due to these properties, nanomaterials (NMs), and nanotechnology have recently revolutionized, and contributed to the solution of various problems faced by the human population, especially in the medical, agricultural, environmental, textile, and food sectors [7], [8]. Nanotechnology offers groundbreaking innovations in many fields such as medicine, environment, energy, textile, and food industries. However, the scope, impacts, and challenges of its applications in these fields have not been fully addressed. While traditional methods are insufficient to address complex problems in these sectors, the unique properties offered by nanotechnology have the potential to provide more effective solutions. This is the main reason why nanotechnology-based approaches are being investigated with increasing interest. Nanotechnology offers groundbreaking applications in many fields such as energy production, health, environment, and food safety etc. [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35]. Solar cell technologies provide low cost, and high efficiency, while biosensors are developing effective solutions for cancer treatment [36], [37]. CO_2 capture processes, and soil remediation technologies contribute to environmental sustainability, while drug delivery, and food safety practices create new opportunities for human health [38]. These technologies go beyond traditional methods, and offer more efficient, and effective solutions. With the advancement of technology day by day, these studies, and applications in the field of nanotechnology have attracted much attention as seen recently [39]. The versatile nature of nanotechnology makes it a groundbreaking tool in the medical, environmental, energy, textile, and food industries. This technology can modify, and control material properties at the nanoscale, and offers innovative solutions that break the limits of traditional methods. Innovative solutions are revolutionizing the field of medicine, and are being used in modern treatment methods through nanomaterials. In particular, nanoparticles are used in drug delivery systems to enable targeted delivery of drugs, reduce side effects, and increase treatment efficacy [40]. Furthermore, nanosensors are being used in the early detection of challenging diseases such as cancer, enabling individualized treatment approaches. Nanotechnology also offers innovative solutions for environmental sustainability. Nanofilters, and nanocatalysts effectively remove pollutants from water, and air, making environmental cleanup processes more efficient [41], [42]. Nanostructured materials used in CO_2 capture systems play an important role in reducing greenhouse gas emissions. In addition, nanotechnology in soil remediation technologies offers innovative approaches that reduce pollution, and increase agricultural productivity [43]. Innovative approaches of nanotechnology are also found in the energy sector. In the energy sector, nanotechnology creates opportunities for clean, and sustainable energy production [44]. Nanostructured materials play an important role in the development of solar panels that provide higher efficiency, and increase capacity, and durability in energy storage systems. At the same time, the use of nanotechnology in areas such as hydrogen production, and fuel cell technologies makes energy conversion processes more efficient. Nanotechnology is also effective in the textile, and food sectors, and offers innovative solutions. There are innovations in the textile sector that increase the functionality, and improve the user experience in nanotechnology applications. Fabrics with antibacterial, water-repellent, or self-cleaning properties are offers broader usage areas in daily life thanks to nanomaterials. In addition, with the opportunities provided by nanotechnology, wearable technology, and smart textiles are being developed, and a bridge is being established decoupling between fashion, and technology. In the food industry, nanotechnology is revolutionizing both production, and consumption processes. Nanomaterials make food packaging more durable, flexible, and biodegradable, while providing solutions that increase freshness, and safety [45]. In addition, nanosensors set a new standard in food safety by rapidly detecting pathogens, and toxic substances in food [46]. As a result, this paper aims to present the innovative applications of nanotechnology in the above-mentioned five sectors under a single roof, providing a comprehensive, and impactful overview. It offers a more transparent, and comprehensive perspective by providing a detailed analysis of the unique properties offered by nanotechnology, the difference between traditional methods, and the sectoral contributions of this technology. The innovative aspect of this paper is that it provides a comprehensive analysis of the potential benefits, and challenges of nanotechnology applications in the medical, environmental, energy, textile, and food industries for both society, and industry. It also makes an important contribution to the literature by discussing the current status, shortcomings, and promising directions of nanotechnology in these fields.

2. Medicinal and biotechnological applications of nanotechnology

2.1. Nanotechnology in biotechnology and medicine

The desire for continuous progress and curiosity of people around the world has led them to the rapidly growing field of nanotechnology in recent years. Especially in line with the increasing needs in the field of health, nanotechnology has the potential to offer ground breaking innovations in medicine, and health services, and covers a wide range of areas, including the development of personalized treatment methods. Nanotechnological applications play a role in the design, synthesis, development, production, and application of materials, and devices using nanostructures with at least one dimension at the nano meter scale, which is one billionth of a meter. Nanostructures at this scale play an important role in our understanding of the properties of molecules, and the materials they interact with. Manipulating molecular structure allows us to manipulate the properties of materials on a large scale. Thanks to nanomaterials, it is also possible to develop molecules that can interact with the body with high specificity (Figure 1). This makes the treatment process shorter, and more effective.

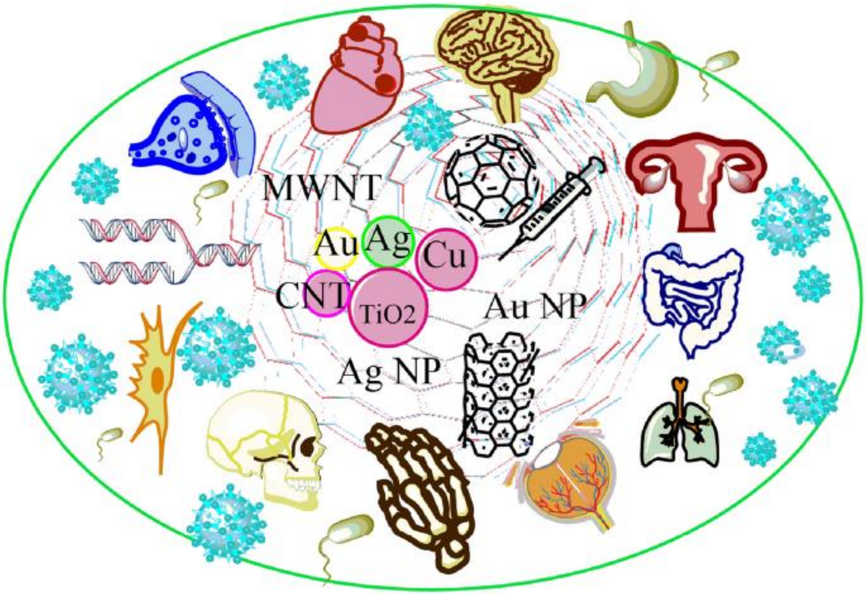

Fig. 1. Demonstration of some nanomaterials used in health applications of nanotechnology [47], Reprinted by permission from Springer Nature.

2.1.1. Applications of nanotechnology in diagnosis

Controlling diseases at an early stage is of vital importance. For this reason, diagnostic sciences today work with nanodevices. In this way, the risk of complications is reduced by taking precautions before the disease progresses, the patient's quality of life is protected, and treatment costs are reduced. Nanoparticles can move easily in the human body due to their size. Thus, they can be designed to be targeted to specific tissues or cells. Thanks to these properties, they can effectively bind with biomarkers by adding various antibodies, and lig, and can be visualized by imaging methods such as magnetic resonance imaging (MRI), computed tomography (CT) scans, and positron emission tomography (PET) scans [48]. This allows it to detect and analyse biological changes in specific areas of the body.

2.1.2. Vaccine development

Vaccines protect against many diseases and are one of the most important inventions of medicine. Throughout history, vaccines have been used in many areas such as preventing various diseases, reducing mortality, and protecting the health of individuals, and communities. However, some negative experiences with traditional vaccines have led scientists to investigate new delivery methods and adjuvants that strengthen the vaccine. Vaccines generally contain an antigen, an adjuvant, and a delivery system. The delivery system is a transportation method that delivers the antigens in the vaccine to the right cells or tissues. Nanotechnology has a particularly important role in vaccine delivery and in the development of adjuvants that stimulate the immune system. Nanotechnology enables the development of many nanocarrier systems such as nanoparticles, nano emulsions, liposomes, polymer micelles, and dendrimers. Vaccines using nanotechnology contain very small nanoparticles. These nanoparticles are designed to carry the antigen directly into immune cells and are being developed to help activate the immune system more effectively [49].

It plays an important role in the control of intracellular infections, especially since it affects T cells, and B cells simultaneously. Particle-based systems preserve the antigenic component of the vaccine while at the same time providing an adjuvant effect. The adjuvant effect of particle-based systems occurs through the uptake of biodegradable particles by APCs (antigen-presenting cells), the continuous supply of antigens, and the activation of innate or adaptive immune responses [49].

This effect can be achieved by creating pathogen-like particles or by utilizing particles that affect the immune system. The success of vaccines in infectious diseases is well known, but vaccine strategies are now recommended in areas such as allergy, cancer, inflammatory disease, and contraception. Vaccine delivery systems developed with nanotechnology are of great importance in this strategy. Among polymer particle nano-delivery systems, polymers based on poly glycolide-co-lactide (PLGA), and poly lactide (PLA) formulations are of great interest [49].

These polymers are more durable than other systems thanks to their biodegradable nature, offer a high antigen load, and are more efficient to be directed to the target area of the body thanks to surface modification. In conclusion, nanotechnology-based vaccine delivery systems offer a promising approach to the treatment of health problems and promise revolutionary innovations in modern medicine.

2.2. Tissue engineering

Tissue engineering aims to create, repair, or replace damaged tissues or organs by combining biologically active molecules. The main goal is to develop materials with a high functional similarity to the body's natural tissues. Researchers in this field use biological components such as stem cells to repair tissues, and organs, allowing damaged areas to heal. However, these processes are generally complex, and problems such as lack of cells, insufficient vascularization, low mechanical strength, and immune response are often encountered. Nanotechnology offers great potential to address these challenges. Nanotechnology is being used in tissue engineering to create materials such as nanofibers, nanopatterns, and nanoparticles [50]. Thanks to nanotechnology techniques, the materials used in tissue engineering have a higher resemblance to natural tissues.

2.2.1. Electrospun nanofibers

Electrospun nanofibers are obtained by drawing a polymer solution or melting from the liquid into fine fibers by applying a high-voltage electric field. In this process, electricity plays a fundamental role by stretching the liquid like silk and determining the structural properties of the material. These nanofibers mimic biological structures, creating scaffolding, and allowing cells to adhere [51]. They are used to engineer tissues such as heart muscle, and bone. In addition, these nanofibers can be used to create blood vessel-like structures. For example, aligned poly(L-lactic-co-ε-caprolactone) nanofibers direct the uniform growth of cells. Furthermore, scaffolds made with materials such as poly(lactic-co-glycolide), and poly(l-lactic acid) have been used to study the growth of neural stem cells [52].

2.2.2. Nanoscale substrates for tissue engineering

Nanoscale substrates for tissue engineering are surfaces with a size between 5-200 nm on which cells can grow, and adhere, but also guide the behavior of cells, support the formation of tissue structures, contribute to the vascularization process, and help the proper functioning of biological functions. Poly(lactic-co-glycolide) (PLGA) is an example of a biomaterial with nanopattern substrates. When the poly(lactic-co-glycolide) nano surface is treated with NaOH, the cell density increases chemically [53]. This allows cells to adhere to surfaces more easily. E-beam lithography is another exemplary technology used to create nano-textured substrates and is utilized in the field of nano-tissue engineering. Because it allows very small, and precise patterns to be created [54].

2.2.3. Self-assembling nanomaterials

Methods to stimulate self-assembly in tissue engineering include biomimetic coating, electrolytic deposition (ELD), and pH induction, using a variety of biomolecular, and inorganic materials such as peptide amphiphile (PA) components, hyaluronan, chitosan, and apatite/amelogenin [50]. Self-assembly mechanisms are processes that enable materials to spontaneously form ordered structures. These mechanisms enable materials to form ordered structures by taking advantage of their hydrophobic, and hydrophilic properties. For example, peptide amphiphiles (PAs) support cell adhesion by forming sheets or fiber structures, and contribute to biological functions [53]. The formation of more complex structures leads to the formation of hydrogels. The soft and water-retaining structure of hydrogels provides cells with an environment similar to natural tissue, which contributes to their growth, and proliferation. This process leads to more durable materials by stabilizing the load balance. Peptide amphiphiles (PA) structures are also an important part of the self-assembly process. These structures promote the self-assembly of materials thanks to their hydrophilic, and hydrophobic regions. The electrolytic deposition (ELD) method enables biomolecules such as collagen to form nanoscale crystalline structures. This method has a wide range of applications in bone tissue engineering and dental crown applications. Electrolytic deposition (ELD) enables biomolecules such as collagen to form nanoscale crystalline structures. This method has a wide range of applications in bone tissue engineering and dental crown applications [55].

2.3. Drug delivery systems

Drug delivery systems are systems that enable the drug to reach the desired tissue or cell in the body. These systems ensure that the drug reaches the target directly, minimizing the risk of damage to healthy cells. A drug delivery system affects the fate of the drug as it will determine the target of the drug, the speed at which it reaches the target, and the amount of absorption. Nanoparticles produced with nanotechnology play an important role in drug delivery systems. These structures are usually designed in sizes of 100 nano meters or less and are made of biodegradable materials such as synthetic polymers, metals, and lipids. Nanoparticles are structures that can be easily taken up into cells due to their size. For therapeutic applications, drugs can be bound to or integrated into the matrix of nanoparticles. The surface of the nanoparticles is then customized with structures such as lig, antibodies, and peptides to recognize target cells. In particular, drug delivery systems produced with nanotechnology are used to provide controlled and targeted treatment through different routes into the body.

2.4. Surgical applications

Nanotechnology has great potential in the surgical field because nanotechnological devices can work very precisely. It enables minimally invasive surgeries with less stress, less scarring, and fewer problems for patients. In addition, nanotechnology makes it possible to perform very precise interventions inside cells.

2.4.1. Orthopedic implant

Orthopedic implants are artificial structures used to support or replace diseased bones, and joints in people with damaged skeletal systems (Figure 2). These implants are frequently used in the treatment of patients who have undergone bone resection for bone malignancies. The inadequacy of traditional implants has led scientists to develop new implants utilizing nanotechnology. Traditional implant materials are insufficient to prevent the spread of cancerous tissue and tumor formation. Implants developed with nanotechnology have features that both support the regeneration of healthy bone tissue and prevent the growth of cancerous cells [47]. Researchers have found that selenium is an element that can inhibit the growth of cancer cells, and slow down the metastasis process. Using nanotechnology, selenium is made more effective by designing, and processing it at nano size. The use of UHMWPE implants in arthroplasty is restricted due to potential fracture concerns. However, thanks to nanotechnology, the addition of carbon nanotubes to this composite material has shown translational success by increasing the durability of the implant [56]. Titanium is a material used in the manufacture of orthopedic implants. Although titanium is preferred to increase osseointegration, it has some limitations and shortcomings. These shortcomings are overcome by nanotechnology [57]. For example, although titanium implants generally have good biocompatibility, the osseointegration process may not always be fast or efficient enough. Nano-textured surfaces and surface modifications promote the adhesion, and proliferation of osteoblast cells, increasing the speed of osseointegration and creating a stronger bond between implant and bone [47].

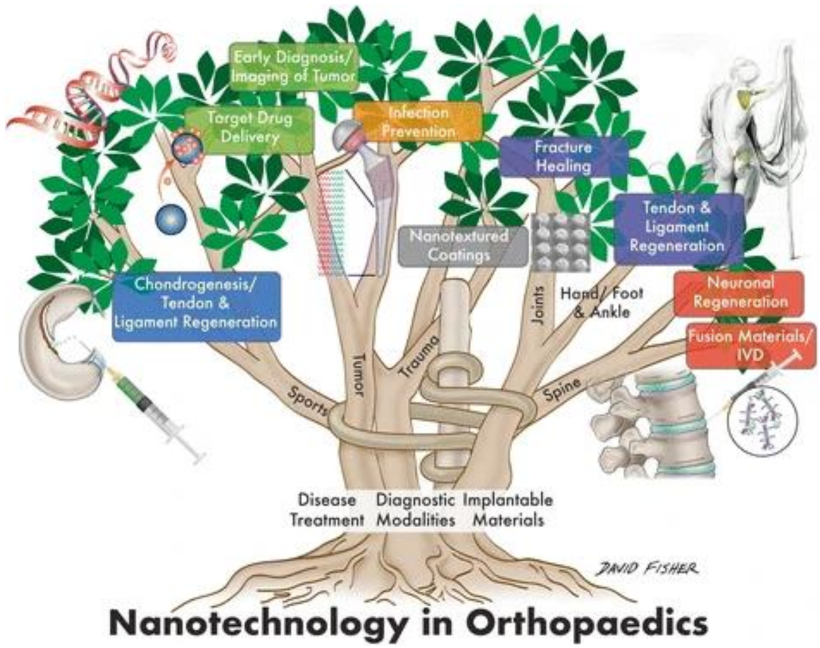

Fig. 2. Diagram showing the fields, and uses of nanotechnology in orthopedics [58]. Reprinted by permission from Springer Nature link.

2.4.2. Nerve tubulisation

Nerve regeneration is an important focus for nanotechnology researchers as well as plastic surgeons. Traumatic injuries causing nerve tissue loss greater than 5mm require autologous nerve grafting for treatment [47]. However, the use of grafts in such cases carries the risk of mobility (e.g. donor site loss, pain). As an alternative, nanoscale structures developed using nanotechnology can be used. The tubular structures produced are designed to support the regeneration of nerves. These tubular structures guide the regrowth of nerve cells [47]. These structures create a suitable environment for the growth of neurons. The surfaces of these nanotechnologically produced structures are modified with special nanostructural coatings that enhance cell adhesion. Furthermore, these tubular structures can be loaded with various biomolecules, and cell types (e.g. embryonic stem cells, Schwann cells, neural stem cells), and released into damaged neural tissue in a controlled, and sustained manner [59]. This controlled release supports the survival of cells and the regeneration of nerve tissue.

2.4.3. Implants, and prostheses

Mastectomy is a procedure performed after breast cancer to prevent the spread of cancerous tissue. In 2012, breast reconstruction was implemented in common plastic surgery procedures. Since then, the implants used have been continuously improved and nanotechnology has been used in this process. Today, to achieve a more effective result, implants are coated with antitumor drugs used in breast cancer treatment. Nanofiber structures come into play here. Specific antitumor drugs are integrated into implants by encapsulating or coating them in nanofiber structures. The aim is to deliver the drugs directly to the cancerous area so that the body suffers less from the side effects of chemotherapy [47]. Nanofiber structures allow the drugs to be released in a controlled manner so that the drugs only act on the cancerous area [47]. Nanotechnology is also used to strengthen silicone implants.

2.4.4. Heart surgery

The heart uses valves to keep blood flowing smoothly through the body. These valves help blood to flow in the right direction. However, in some cases, these valves may not function properly, and in this case, the faulty valves may need to be identified, and repaired or replaced surgically [60]. In this case, nanotechnology is used to replace the structure of the valves with tiny gold rods known as nanomaterials [47]. Nanotechnology can improve the longevity of valves, and their ability to repair themselves when necessary. Such innovations offer safer and more effective treatment options in cardiac surgery.

2.4.5. Soft tissue repair

Wounds and burns usually take a long time to heal because they damage the tissues under the skin. Since open wounds occur during this process, the risk of infection is high. The body provides tissue repair by the spontaneous proliferation of cells. However, it is difficult for the body to recover from deep wounds. Nanotechnology offers various innovative solutions to overcome these challenges. In surgical interventions, nanotechnology is used as an effective tool, especially for soft tissue repair, and healing. Wound and burn care are two clinical care areas that benefit from nanotechnology. In this field, nanofibers are produced using nanoscale production techniques. Nanofibers are thin and filamentous structures, three-dimensional structures that mimic the natural extracellular matrix (ECM) [61]. Nanofibers provide the properties needed for tissue repair, such as temperature control, fluid absorption, and mechanical integrity [47]. Research has shown that collagen-based nanofibers have a great contribution to wound healing. In particular, nanofibers modified with epidermal growth factor (EGF) are known to significantly optimize the wound healing process by accelerating keratinocyte proliferation in diabetic individuals [62]. Chitin and chitosan are polysaccharide nanocrystals derived from the exoskeleton of seashells and are used in various formulations to promote the wound-healing process [47]. In various mouse experiments, these substances have been observed to shorten the healing time of wounds and leave less scarring.

2.4.6. Surgical instruments

Nanotechnology is widely used to improve the performance and durability of surgical instruments. Surgical blades are coated with nanomaterials such as diamonds to make their surfaces smoother. This coating prevents the blades from sticking to tissues, allowing surgical procedures to be performed more easily, and effectively. Similarly, sewing needles contain nano-sized particles (1-10 mm semi-crystals) that improve the material structure and increase their physical properties. In this way, the needles become stronger, and more durable, offering a more reliable use in surgical.

3. Environmental applications of nanotechnology

From the past to the present, mankind has constantly struggled with environmental problems. With the development of nanotechnology, solutions to these problems have been found, and great improvements have been made to environmental problems. Problems such as environmental pollution, water pollution, soil pollution, and air pollution have been minimized by using nanotechnology. This change created by nanotechnology in environmental problems promises greater goals for the future. Sustainable agriculture, carbon capture, smart sensors, biodegradable nanomaterials, energy conversion, and efficiency, water treatment, pollution reduction, waste management, and soil remediation are some examples of environmental applications of nanotechnology (Figure 3).

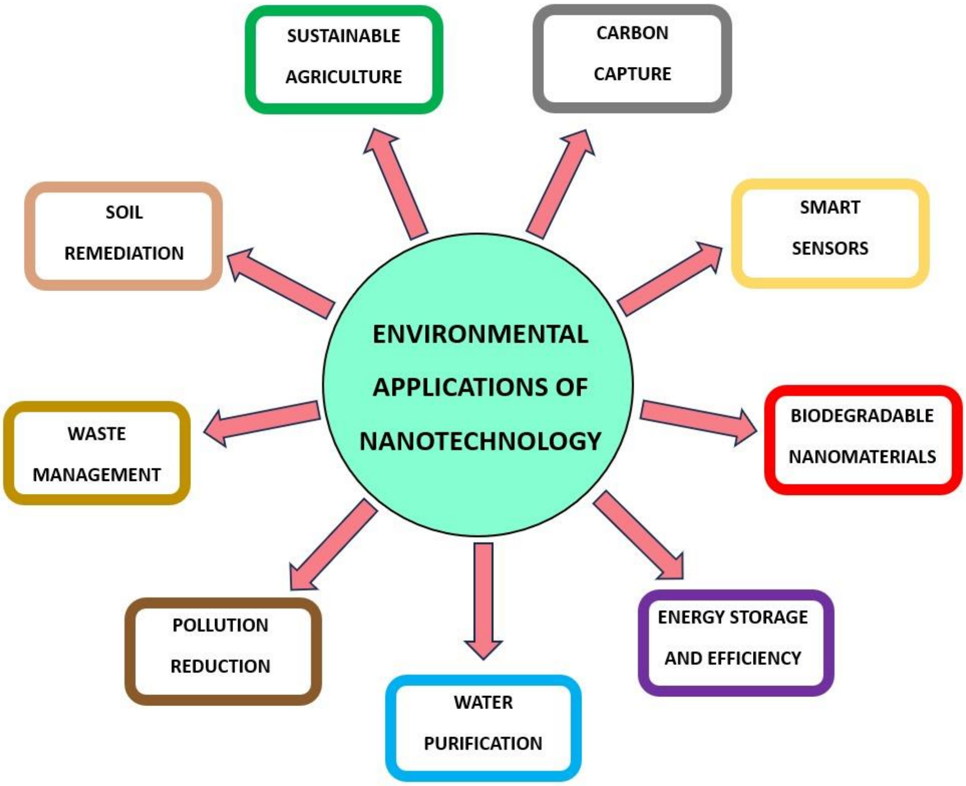

Fig. 3. Applications of nanotechnology in the environmental field.

3.1. Sustainable agriculture

Nanotechnology enables careful control of nutrients to make them more efficient. In this context, the various attributes, and applications of nanomaterials are being evaluated in detail, as well as their health, and environmental risks. It is emphasized that the toxicity of NPs (apart from size) is influenced by their chemical structure, shape, surface properties, charge, behavior, degree of particle agglomeration or segregation, etc. These elements are relevant for engineering nanoparticles (NPs) [29]. Therefore, nanomaterials with different sizes or shapes, and the same chemical structure are differentiated in terms of toxicity level. Nanotechnology studies are very valuable and indispensable for sustainable agriculture. Nanotubes, fullerenes, biosensors, controlled delivery systems, nanofiltration, etc. are applied in this branch. It is argued that this technology contributes to the resource management of agricultural areas, the transport of pesticides to plants, and soil fertility-style systems. It is also used in biomass, and agricultural waste utilization, food processing, and packaging, and risk analysis. Increasingly, nano sensors are becoming common in agriculture as they are powerful, fast, and accurate for environmental monitoring of pollution in soil, and water. Many sensors for nano-sensing technology, such as biosensors, electrochemical sensors, optical sensors, and devices, have been recognized as the main tools for detecting heavy metals in the trace range. Nanomaterials not only enable the catalysis of waste and toxic substances but also the efficiency of microorganisms in decomposing these substances. Bioremediation selects living organisms to remove hazardous, and harmful components in agricultural soil, and water, or to make them less harmful. Specific terms such as bioremediation (beneficial microbes), phytoremediation (plants), and mycoremediation (fungi) are more commonly used. Among these methods, bioremediation removes heavy metals from soil, and water through microorganisms in a way that is beneficial to nature. Agricultural bioremediation supports sustainable development technologies that restore the natural, and pristine state of the soil. The relationship of nanoscale materials to remove the toxic component of agricultural soil, and make it sustainable is becoming an interesting phenomenon [63].

3.2. Carbon capture

The dangers posed by greenhouse gases, and global warming are well known. Among the many greenhouse gases, the most interesting are fluorinated gases such as carbon dioxide (CO_2), methane (CH_4), and sulfur hexafluoride (SF_6). Greenhouse gases are emitted during the combustion of fuel for energy or heat, during chemical reactions, or from farmed animals. Nanotechnology applications provide useful solutions for efficient carbon capture and gas separation. There has been a lot of research recently to design carbon capture systems to efficiently remove harmful greenhouse gases from the majority of emissions, especially when it comes to fuel combustion and chemical reactions. Rather than capturing all the gases at once, this aims to selectively remove them from the emission stream [64]. Forests help reduce greenhouse gases, and global temperature rise by storing carbon. Carbon is stored in trees through photosynthesis, contributing about 50% of the dry wood mass. Wood is therefore extremely important for improving nature's capacity to capture, and store carbon. Emerging wood nanotechnologies are highlighted for their potential to create high-performance products that can replace fossil-based plastics. It also covers technologies in engineered wood products, including densification, chemical modification, and mineralization, which aim to improve wood carbon storage. The economic, and carbon mitigation impact of woody biomass is briefly examined, showing how sustainable management of forests, and wood can help reduce greenhouse gas emissions, and global warming [65]. With a wide range of materials and numerous benefits, different types of nanomaterials are being studied for their ability to capture carbon, and separate gases from emissions [64].

3.3. *Smart sensors*

Pathogenic bacteria that cause infectious diseases, especially antibiotic-resistant ones, threaten global health. Currently, bacterial contamination is largely determined through traditional culture practices, which are limited by the time required for processing by specialized users, and the availability of facilities. Based on this, real-time, and continuous monitoring of pathogen levels is required to obtain important information that can help healthcare institutions to prevent, and control pathogen-containing outbreaks. Nanotechnology-based smart sensors are revolutionizing the rapid, and timely detection of pathogens at the point of care. Due to their unique optical, magnetic, and electrical properties, nanomaterials are of great importance in bacterial detection. Carbon nanoparticles, various types of nanocomposites, and metallic, and metal oxide nanoparticles are known to be the most remarkable nanomaterials for microbial detection. These pioneering methods, combined with state-of-the-art technologies, wireless communication, and machine learning, will have a place in infectious disease diagnostics. This work highlights the recent advances in the efficient application of different nanoparticles for the detection of bacteria. Initially, it illustrates the fundamental concepts, and mechanisms underlying the design, and strategic approaches of nanoparticle-based diagnostic platforms. Important work activities in the detection of bacteria in vitro, and in vivo are indicated. In this context, a general discussion covers the most widely used techniques for bacterial identification, including pioneering work focused on detecting bacteria at the single-cell level. In conclusion, an exploration of the existing problems in this field as well as a future perspective with proposed solutions is continued [66].

3.4. Biodegradable nanomaterials

In today's world, there is a dominant focus on the management of non-biodegradable waste, which requires more complex, and sophisticated procedures than the management of biodegradable waste. This emphasis often overshadows the fact that biodegradable waste, when subjected to relatively simple processing techniques, has significant potential to deliver societal benefits. Researchers are vigorously pursuing sustainable nanotechnology pathways by utilizing biodegradable waste to prepare nanomaterials, thus bridging the gap between waste management and technological progress. The integration of biodegradable waste into the development of nanomaterials demonstrates the promising intersection of environmental sustainability and innovation. Polarization, a process using biological waste, is leading to the development of safer, and non-hazardous green methods for the synthesis of nanoparticles. This approach covers a variety of sources, and applications, from therapeutics, and the food industry to water treatment solutions. The review delves deep into the advantages, and disadvantages of nanoparticles derived from biowaste, and ultimately highlights potential advancements in their application. In the current scenario, the synergistic combination of green synthesis methods and biowaste utilization holds the promise of a wide range of applications in the field of nanotechnology. However, for these advances to be fully realized, challenges related to mass-scale industrial production need to be addressed. With these considerations in mind, the review also focuses on the cost-effective synthesis of metal, and metal oxide nanoparticles, and highlights the importance of economically viable solutions [67].

3.5. Energy storage, transformation, and efficiency

Recently, nanotechnology has made significant advances, especially in the storage, and conversion of electrical energy, which has become a critical area of investigation. Nanotechnology is seen as a crucial technology in the application of energy conversion, storage devices, and energy efficiency, especially for portable and smart devices. This advanced technology is crucial in overcoming the challenges posed by limited and insufficient energy resources. The use of nanomaterials paves the way for the creation of self-propelled devices. Various nanomaterials such as nano-chains, nanofibers, and nanotubes are involved in the development of fuel cells. In addition, nanotechnology is significantly impacting, and leaving a deep imprint on other application areas in the energy sector, including solar cells, supercapacitors, and smart batteries. Nanomaterials critically improve the efficiency of heating, and lighting due to their larger surface area, allowing for more storage space, and offering a more sustainable, environmentally friendly alternative way forward. The inclusion of nanoparticle fuel additives is highly advantageous in minimizing carbon emissions associated with fuel consumption. Furthermore, nanomaterials have a significant potential for shortening diffusion lengths, thereby improving the kinetic performance of storage devices. In addition to nanoscale heat-, and corrosion-resistant protection, the composition of nano-optimized membranes significantly improves system efficiency [68].

3.6. Water purification

Nanotechnology is of vital importance in the field of water treatment, primarily due to the environmentally remarkable chemical and physical properties of nanomaterials. These properties include but are not limited to the large specific surface area, chemical activity, adsorption, and large absorption capacities of nanoparticles, increasing the resistance of materials to mechanical stress or weathering. The application of nanotechnology, groundwater desalination, brine treatment, and wastewater treatment reviews this field in detail with three distinct features, in particular their sustainability. The lack of clean drinking water is a dangerous global challenge in the current era. It is assumed that around 1.2 billion individuals have difficult access to safe and safe drinking water. In addition, around 2.6 billion people are unable to meet their basic hygiene needs due to a lack of sufficient water. Comprehensive systems require robust infrastructure, and advanced levels of engineering expertise, leading to excessive implementation time, significant costs, and inefficiencies, especially when rapid deployment and urgently needed solutions are required. In such situations, nanotechnology holds significant promise. This high-tech field focuses on manipulating matter at the nano meters scale to develop innovative structures, devices, and systems. At the nanoscale level, particles have distinctive chemical, physical, biological, optical, magnetic, and electrical properties that are unique compared to larger particles. The enhanced surface area of nanoparticles helps in the removal, and absorption process of pollutants such as organic, and inorganic solutes, heavy metals such as mercury, lead, arsenic, and cadmium, as well as organic poisons responsible for waterborne health problems such as cholera, and typhoid. Nanotechnology is useful in the rapid detection, and removal of these contaminants, and provides a pathway for cost-effective treatment in emergencies. This research highlights critical advances in the application of nanotechnology for the sustainable treatment of wastewater, groundwater, and brine. Improving the methodology of highly advanced nanotechnology provides new possibilities for advancing water, and wastewater treatment by challenging the capabilities of conventional process engineering. Nanotechnology has a wide range of applications in classical water treatment methods such as coagulation, sedimentation, filtration, disinfection, decontamination, and desalination; nanoscale filtration techniques, adsorption of pollutants onto nanoparticles (NPs), and catalytic degradation of pollutants as nanoparticles. Recently, many new and different nanomaterials have been developed and used for water, and wastewater treatment. This category includes carbon nanotubes, cellulosic nanomaterials, polymer nanocomposites, metallic nanoparticles, nano zeolites, graphene, graphene oxide as well as carbon, and graphene quantum dots. The challenge of keeping chemical toxins away from the surface, subsurface, and different situations is significant, especially when applying them appropriately, and in situ. The main goal is to realize these tasks quickly, efficiently, and cost-effectively. In summary, wastewater treatment techniques based on nanotechnology exhibit high performance in removing pollutants and contributing to the recycling process to produce treated water. This approach leads to a reduction in labor time, and industrial costs while solving multiple ecological problems [69].

3.7. Pollution reduction

Population growth, and industrial residues released from developed sectors are disrupting the ecological balance. Climate change and environmental pollution are the most criticized issues globally. Environmental pollution poses serious threats to our lives as it can cause many dangerous diseases. In this case, pollutants must be degraded immediately. Accordingly, it is almost impossible to break down some pollutants, and much time is needed for remediation. To address this problem, the application of nanotechnology provides a promising solution. Nanotechnology, thanks to its large surface areas, active sites, and large functional groups, can neutralize pollutants or sufficiently eliminate the hazard. The effectiveness of nanotechnology in this context is attributed to its large surface areas, active sites, and sufficient functional groups. In addition, strong surface complexes can be produced with many different pollutants. Various nanomaterials within inorganic, carbon-based, and polymeric materials are utilized in the cleanup of environmental pollutants. Such innovative materials are efficient in the purification of pollutants such as dyes, organophosphorus compounds, heavy metals, chlorinated, volatile organic compounds, and halogenated herbicides. Furthermore, processes such as the adsorption or reduction of organic pollutants, and heavy metal ions by photocatalytic reduction are often recognized as some of the critical methods to minimize the concentration of pollutants in the environment. In this context, the review explores the ongoing development of nano-catalysts for the remediation of environmental pollutants, which should ensure a healthy, and safe environment for the future [70].

3.8. Waste management

Waste management is challenged by the sudden growth in waste generation and the emergence of new types of waste. To address this problem, innovative technologies such as nanotechnology are gaining importance. Nanotechnology makes use of nanomaterials that are less than 1 to 100 nano meters in size. The small size of these materials increases their sensitivity in processes such as adsorption, and oxidation/reduction. The use of nanotechnology plays an important role in creating new materials to replace existing raw materials, and in providing new solutions for waste recovery, and removal. Furthermore, nanofiltration has been confirmed to be useful for the removal of metals, hazardous wastes, and non-biodegradable leachate materials [71].

3.9. *Soil remediation*

Global issues such as soil degradation, pollution, and loss of soil benefits due to industrialization, and intensive agricultural practices pose a serious challenge to agricultural productivity and sustainability. Multiple technological developments are underway to improve soils and promote the usefulness of harmful soils. These methods often fall short of restoring or improving soil health to the desired level due to higher than necessary costs, non-functionality in real-world settings, and, to a lesser extent, significant labor requirements. Recent advances in nanotechnology are ensuring improved soil quality, and crop yields while supporting environmental sustainability. Nanomaterials (NMs) in soils maximize their ability to influence and activate rhizospheric microbes or agriculturally important microbes. At the same time, they enable the successful delivery of nutrients to plants. This improves root structures and promotes crop growth. Thus, nanotechnology opens up new possibilities to positively improve soil fertility [72]. Agri-nanotechnology is an emerging field where nanotechnological methods are introducing many nanomaterials (NMs) such as nano pesticides, nano herbicides, nano fertilizers, and various nano agrochemicals to improve agricultural management. The application of these nano-fabricated products has the potential to improve the shelf life, stability, bioavailability, safety, and environmental sustainability of active ingredients for sustained release. Nanoscale modifications of their distinctive aspects, such as bulk or surface, hold considerable promise for efficiently enhancing agricultural productivity. Since NMs enhance the resistance systems of plants under stressful conditions, they are seen as effective and promising tools to overcome challenges in sustainable agricultural production. Due to their exceptional qualities, and applications, nano-enabled products are being developed, and applied in various sectors, including agriculture [73]. Balancing the benefits of agricultural nanotechnology with its environmental impacts is of paramount importance. Ongoing research, stringent regulations, and wide-angle reviews play a vital role in ensuring that these developments support sustainable agricultural production while minimizing potential environmental risks. By responsibly harnessing the capacity of nanotechnology, it contributes to a more sustainable and productive agricultural tomorrow.

3.10. Potential risks in environmental applications of nanotechnology

Nanotechnology, the manipulation of matter at the atomic and molecular level is revolutionizing industries ranging from medicine to electronics. However, its environmental impact is a growing concern. While nanotechnology offers significant benefits, it also poses potential risks to the environment. Nanoparticles can be toxic to multiple organisms, including bacteria, plants, animals, and humans. Studies show that nanoparticles can cause oxidative stress, DNA damage, and inflammatory responses. Nanoparticles can accumulate in the tissues of organisms, leading to potential long-term health problems. Some nanoparticles are resistant to natural degradation processes, resulting in their transience in the environment. The release of nanoparticles can adversely affect ecosystem structure by affecting organism growth, and reproduction. Nanoparticles are emitted into the air and water during the production, and destruction of nanomaterials. Nanoparticles are used in many consumer products, including sunscreens, cosmetics, and clothing, leading to their release into the environment. Nanoparticles applied in agriculture, such as those used in pesticides, and fertilizers, can be harmful to soil, and water resources.

4. Nanotechnology, and energy

Nanotechnology stands out as an indispensable solution for alternative and sustainable energy sources. Nanotechnology applications are transforming the energy l, landscape, and revolutionizing energy storage in batteries by improving the performance of solar cells [31]. In this way, it also facilitates the production of clean fuels [74]. The energy sector, including energy resources, energy conversion, energy distribution, and energy storage, affects every aspect of the chain. It has significant potential to develop both fossil, and nuclear fuels, and renewable energy sources such as geothermal, solar, wind, hydroelectric, tidal, and biomass. High-performance nanomaterials are ideal for creating lighter, and more durable rotor blades for wind, and tidal power plants. They can also be used as wear, and corrosion protection layers for mechanically pressurized components such as bearings, and gearboxes [75], [76].

4.1. Nanotechnology and energy transformation

Nanotechnology plays a major role in power plants, turbine materials, and thermoelectric energy conversion. Power plants convert heat generated by fossil fuels or nuclear energy into mechanical energy through turbines, and then into electrical energy. However, this requires the use of materials that can withstand and both heat and corrosion. Conventional materials such as steel, and metal alloys have limitations in the temperatures they can withstand. These materials are lightweight and maintain their strength at high temperatures. To improve the performance of these materials further in extremely hot environments, nano-protective layers can be applied to the materials. These micro-layers serve to prevent corrosion caused by friction and heat from the gases inside the turbines. They help to protect turbines by acting as thermal insulators, provide higher operating temperatures, and increase the overall efficiency of power plants, and aircraft engines without causing rapid wear of the materials used [4], [77]. In many systems, a significant amount of heat is wasted, such as the heat generated by car engines or even human body heat. Instead of allowing this heat energy to dissipate into the environment, nanoscale semiconductors can be used to prevent it. Special nanomaterials are being designed to convert temperature differences into electrical energy through a process known as the thermoelectric effect. Precisely engineered at the nanoscale, these nanomaterials increase thermal efficiency by improving the transfer of heat, and electrical charges within the material. In addition, the heat generated by the human body can also be used to power small electronic devices used in smart textiles, including garments embedded with health sensors or other electronic features [6].

4.2. Nanotechnology, and energy distribution

One of the biggest problems in energy distribution networks is the energy loss that occurs during the transmission of electricity through cables. This loss negatively affects the efficiency of the system, while at the same time increasing costs and energy requirements. Nanomaterials such as carbon nanotubes offer a potential solution due to their unique electrical conductivity properties, making them excellent candidates for improving the performance of cables and power lines. Carbon nanotubes are nanoparticles made of carbon sheets wrapped in extremely thin tubes. These tubes have exceptional electrical conductivity properties that enable them to transfer electrons quickly and efficiently with low resistance compared to conventional materials such as copper. Thus, energy loss during transmission is minimized and can significantly improve the efficiency of the power grid. Carbon nanotubes play a vital role in power distribution networks through the use of nano sensors as well as carbon nanotubes. Ultra-small sensors can continuously monitor currents, temperatures, pressures, and other critical variables in the power grid. Thanks to their high accuracy, and compact size, nano sensors can be widely deployed throughout the grid. They also facilitate real-time monitoring and analysis of potential changes or problems. This data enables smart control, and immediate response to emergencies, reducing outages and increasing the stability of the grid. The challenges facing power grids require complex control mechanisms to manage changing loads, and unexpected problems. Nanoelectronics is emerging as an important part of the solution, encompassing the design of nano electronic components that can effectively manage energy flows with high efficiency and precise control over distribution processes. These components improve the efficiency of energy conversion, and distribution, reducing overall energy consumption, and increasing operational efficiency. By integrating nanomaterials, smart sensors, and nanoelectronics, a highly efficient, and sustainable advanced power distribution network is being created. This network can quickly respond to, and predict failures while automatically rebalancing power distribution. In this way, nanotechnology provides a comprehensive, and effective solution to minimize energy losses and improve the performance of power grids, taking an important step towards achieving smart, and sustainable grids for the future.[78].

4.3. Nanotechnology and energy storage

Nanotechnology is making significant advances in the development of electrical energy storage solutions, particularly in batteries, and supercapacitors. Progress in this field is largely based on nanomaterials with unique properties not found in conventional materials. Among advanced battery technologies, lithium-ion batteries, and due to their ability to provide high voltage, energy density, and sufficient power, making them ideal for energy storage in electronic devices, and electric cars. Batteries containing nanotechnology can withstand more charge and discharge cycles. This extends their lifespan, making them a cost-effective, and practical option. Nanomaterials for fuel cells used in portable electronic devices offer innovative solutions, especially nano porous metal-organic compounds. These compounds have a fine porous structure that facilitates the chemical reactions necessary for energy production, leading to increased efficiency, and reduced costs. By incorporating these materials into fuel cells, the performance of portable devices can be significantly improved, providing stable and continuous energy sources without the need for frequent recharging. [79], [80].

4.4. Negative ımpacts of nanotechnology in energy

The field of nanotechnology brings many advancements to the energy sector with its ability to increase efficiency, reduce costs, and improve clean, and sustainable energy production. In addition to these developments, there are also significant challenges and risks associated with the use of this technology in the energy sector. These challenges can be categorized as environmental, health, technical, and economic risks (Figure 4).

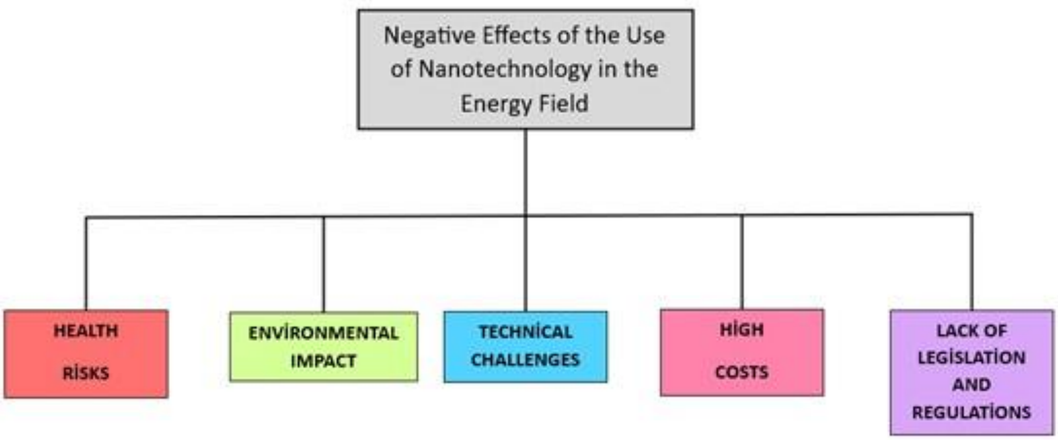

Fig. 4. Illustration of the negative impacts of the use of nanotechnology in the field of energy.

4.4.1. Health risks

The use of nanomaterials in the energy sector (such as batteries, solar cells, or catalysts) can pose health risks. Nanoparticles are extremely small, and can easily penetrate the body's tissues, and cells. Nanoparticles entering the respiratory tract or bloodstream are therefore of concern as they can lead to infections, and other health problems [10].

4.4.2. Environmental impact

Nanoparticles can threaten the environment, especially when not h, handled safely. Nano-waste generated during the production of solar panels, and nano-batteries can leach into water, air, or soil, affecting living organisms, and disrupting natural food chains, leading to environmental pollution. In addition, some nanomaterials are difficult to decompose, leading to their accumulation in the environment over long periods [10].

4.4.3. Technical challenges

While nanotechnology has the potential to improve energy efficiency, producing nanoparticles with high precision requires advanced technologies and significant investments. This technical complexity can cause instability of the properties of nanomaterials over time, reducing their performance, and efficiency. Furthermore, scaling up the application of nanotechnology poses challenges that require further development to reduce costs, and ensure practical use in various industrial applications [10].

4.4.4. High costs

The production and development of nanomaterials are costly and require advanced equipment and technologies. Despite the high efficiency that can be achieved with nanotechnology, these costs can make the technology out of reach for many small companies, and institutions. This limitation can hinder the widespread adoption of the technology, and delay the realization of its full benefits in the energy sector [10].

4.4.5. Lack of legislation, and regulations

Legislation, and regulations governing the use, and distribution of nanomaterials are still in their infancy, especially about energy applications. Existing laws are often insufficient to fully protect the environment, and human health, which poses risks due to the lack of strict standards for the management of nanomaterials. This lack of regulation can lead to misuse of nanomaterials, and disregard for safe disposal or recycling methods [10].

5. Nanotechnology in textile industry

5.1. Textile industry and nanotechnology

Dressing is one of the most basic needs of humanity as long as life exists for living things. Humans have been living collectively from the past to the present. In this process, they see dressing as a need to adapt to social and environmental conditions. Textile, which exists with this need of people, is constantly developing, and gaining an industrial identity in the face of individuals' desire to look nice in the societies they live in. For these reasons, the textile industry is one of the oldest industrial fields. Starting with the fiber, the process in which the yarn and the product come to the fabric stage is examined within the scope of textile, and the part from the fabric to the stage of clothing is examined within the ready-made textile industry. The textile industry is part of the production network of the ready-to-wear clothing industry and offers a wide variety of products. In addition, the textile industry does not only focus on clothing but also develops various products according to all the needs of consumers [81]. The textile industry has been constantly developing, and reaching more advanced dimensions with such innovations from the past to the present. Nanotechnology used in the textile industry is one of these innovations. At the same time, nanotechnology provides multiple opportunities for the fabrics used in this industry, as it aims to be environmentally friendly in its applications in the textile industry, to save energy, and water, and to reduce the cost economically. The fact that the fabrics used in the textile industry contain features such as their weight, and large surface area provides an ideal infrastructure for the applications of nanotechnology in the textile industry. Especially the large surface area of fabrics provides a great advantage in the formation of the relationship between nanotechnology, and the textile industry. The integration of nanomaterials into textiles is the basis of numerous researches aiming to improve the durability, aesthetic properties, and functional performance of fabrics. Thanks to these technologies, textiles can be endowed with various superior properties such as water repellency, antibacterial properties, UV protection, antistatic properties, self-cleaning properties, wrinkle resistance, etc. [82].

5.2. Production methods of nanotechnology in textile industry

The stages in the production of nano-engineered textiles are different. The main difference between them is whether unnatural nanoparticles are processed into fibers or other textile materials, whether surface film is used on fabric surfaces, and whether nanoparticles are used in nano-sized fibers, and other textile products. Various textile fabrics in nano coatings consist of filming methods. This method is one of the most widely used methods of integrating nanoparticles into fabrics, and clothing. Nanotechnology enables the development of multifunctional, durable, and smart products in the textile industry by using various techniques such as these. Coating compositions containing nanoparticles, surfactants, and carrier media are used to modify the surface properties of fabrics. Properties such as durability and weather resistance of fabrics are enhanced by methods such as sol-gel, layer-by-layer, and plasma polymerization. Nanofibers are produced by electrospinning, where fibers are reduced to nano-size. In addition, alternative methods such as split spinning are still being developed. Nanocomposite fabrics st, and out with their superior mechanical, and performance properties, while nanofibers, whiskers, and nanofoils are used for structural modifications. These fabrics have properties such as high surface area, thin layers, and good filtration, and are used in a wide range of fields from medical textiles to smart buildings. Innovative products such as heating and cooling textiles, conductive and communication textiles, digital fashion and chromatic textiles are shaping the future of the textile industry [83].

5.3. Applications of nanotechnology in textile industry

Nanotechnology offers innovative solutions to increase the surface, and structural properties of materials in the textile industry, and provides textile products with advanced properties. Nanomaterials and coating techniques improve the functional and aesthetic qualities of textiles by enabling applications such as antibacterial properties, UV protection, antistatic properties, self-cleaning properties, and anti-wrinkle properties (Figure 5). Such innovations improve the performance of textiles used in both daily life and technical fields, while also supporting sustainability [84], [85].

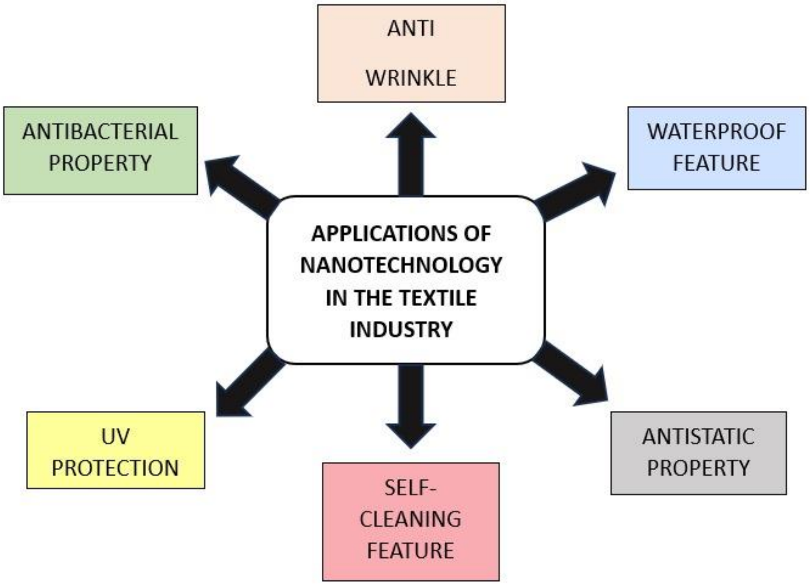

Fig. 5. Applications of nanotechnology in the textile industry.

5.3.1. Waterproof feature

Nanotextiles improve the hydrophobic properties of fabrics produced in the textile industry by forming hydrogen, and carbon compound nanoclusters one thousand the size of an ordinary cotton fiber. While these nanoclusters give the fabric a velvety effect, the widths between the flagella are too small compared to ordinary water droplets, and too large compared to water molecules [84]. In this way, water droplets remain on the outer surface of the whips, and fabrics. Thanks to this feature, the breathable structure of the fabrics is preserved, and long-term use of the fabrics is ensured [82], [83], [86], [87], [88]. Technologies such as Nanosphere repel water and prevent dirt particles from sticking by mimicking the mechanism found in lotus leaves and creating three-dimensional surface structures. In addition, nano-sized nanoparticles such as TiO_2, ZnO, Fe_2O_3, and SiO_2 are also used to increase the waterproof properties and improve the hydrophobicity of fabrics [82], [86], [87]. These nanoparticles create roughness on the outer surface of the fabric, allowing the collection of water droplets, but also small dirt particles.

5.3.2. UV resistance

The textile industry is taking advantage of the possibilities offered by nanotechnology to offer improved products that can protect the wearer from environmental conditions, and harmful UV radiation. Since UV radiation (150-400 nm wavelength) can be harmful to the skin, it is a great advantage for fabrics to absorb, and scatter these rays [83], [86], [89]. Inorganic semiconductor oxides such as ZnO, SiO_2, TiO_2, and Al_2O_3 have been used to improve UV-blocking properties in fabrics (Figure 6) [90]. Among these inorganic semiconductor oxides, TiO_2, and ZnO are more widely used than other semiconductor oxides, and provide much more effective UV protection than macro-sized materials. This is because nanoparticles have a larger surface area and can absorb, and scatter UV light more intensively [82], [91], [92]. In particular, ZnO, and TiO_2 nanoparticles of 20-40 nm in size effectively block UV radiation at wavelengths of 200-400 nm [87], [92]. These nanoparticles, applied to the fabric surface by techniques such as the sol-gel procedure, impart wash-resistant UV protection properties to fabrics [84]. At the same time, thanks to the photocatalytic, electrical, anti-bacterial, and biocompatible properties of ZnO, fabrics gain not only UV-blocking properties but also stain resistance, water repellence and antibacterial properties [87]. 10-50 nm size variants of ZnO and TiO_2 nanorods provide a high level of UV protection factor (UPF) when integrated into cotton fabrics [82],[91]. Integration of nanoparticles into the outer surface of the fabric by various methods plays a major role in enhancing this property. For example, when the coating process is applied to integrate nanoparticles into fabrics, nanoparticles are not only integrated into the outer layer but also integrated into the internal structure of the fabrics. This prevents the nanoparticles from remaining in the outer layer of the fabrics, thus preventing the absorption of UV rays in the fabrics. In order to prevent such a situation, nanoparticles should only be applied to the areas of fabrics directly exposed to UV rays. The spraying method used in such applications is one of the most effective methods of coating the outer surface of the fabric with nanoparticles [82].

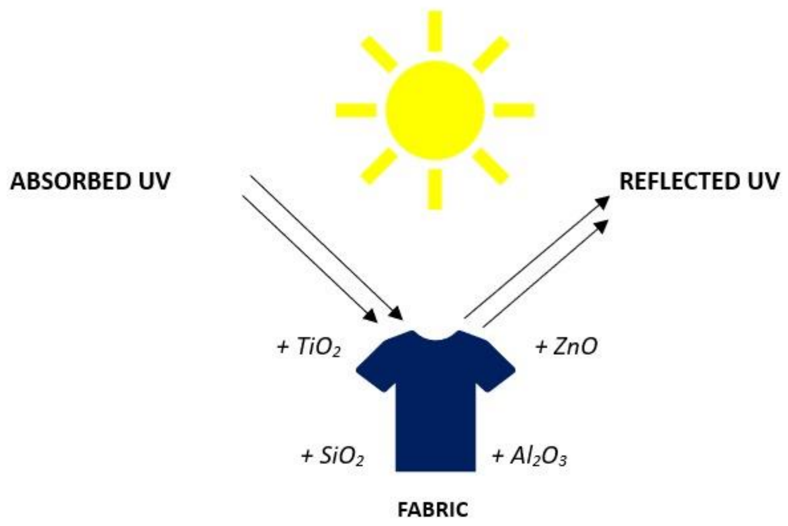

Fig. 6. Illustration of UV blocking properties of fabrics treated with ZnO, TiO_2, SiO_2, and Al_2O_3 nanomaterials.

5.3.4. Antibacterial feature

In the modern textile industry, the application of antibacterial properties to fabrics is becoming increasingly important for both protecting consumer health and improving product performance. In daily use, fabrics can create a suitable environment for the growth of microbial agents due to factors such as perspiration, environmental moisture, and microorganisms. This can lead to undesirable consequences such as bad odors, skin infections, and reduced durability of products. Fabrics with antibacterial properties are considered essential to prevent these problems, especially in products such as sportswear, socks, bedding, and medical textiles [84]. Compared to conventional antibacterial treatments in antibacterial applications of textiles, nanomaterials offer unique advantages such as larger surface area, high reactivity, and long-term efficacy. Nanoscale silver (Ag), titanium dioxide (TiO_2), zinc oxide (ZnO), chitosan, triclosan, copper (Cu), and boron (B) nanoparticles are widely used to impart antimicrobial properties to textiles [82], [91] [93]. Silver (Ag) nanoparticles have the most effective antimicrobial properties compared to other nanoparticles. This nanoparticle inhibits DNA replication, and enzyme activities by interacting with phosphoruscontaining parts of the DNA of microorganisms and sulfur-containing proteins of enzymes [94]. This provides a strong antimicrobial effect. Silver nanoparticles are mostly used in textile products close to the skin such as socks and in health applications, while TiO_2, and ZnO nanoparticles play a role in decomposing odors, bacteria, and viruses by oxidizing organic substances since they have photocatalytic effect. Boron nanoparticles are effective against Gram-positive, and Gram-negative bacteria, and change the surface properties of textile material. Copper nanoparticles synthesized from some plant extracts were also found to be effective against microorganisms. Antimicrobial properties in fabrics can be achieved by adding antibacterial substances into the fiber during the fiber formation process or by finishing processes. In the fiber forming process, the antibacterial agent is added to the polymer or fiber solution before spinning in the yarn forming stage. Thus, the substance is integrated into the polymer structure of the fiber, and provides antibacterial properties in every part of the fabric. With finishing processes, antibacterial effects are achieved by using methods such as spraying, impregnation or coating. These methods increase the effectiveness of antibacterial agents on the surface of the fabric, and inhibit the growth of microorganisms [95].

5.3.5. Antistatic feature

Synthetic fibres, especially materials such as polyester, and nylon, accumulate static charges due to their low moisture content. The accumulation of static charges can cause multiple problems in textiles. For example, while the accumulation of electrical charges in fabrics can cause discomfort to users, the sudden discharge of these charges can damage electronic devices or pose great risks such as fire, and explosion [87],[96]. Nanomaterials are very effective in solving these problems, and create antistatic effects by removing static electricity from fabrics. Especially nanomaterials such as nanoscale TiO_2, ZnO, antimony-containing tin oxide (ATO), and silane nanosol effectively neutralize static charges by increasing the electrical conductivity of fabrics [83], [88], [91], [93]. These materials increase the safety of the products by dissipating the static electricity accumulated in the fabrics and provide comfort for the users in the use of the products [97]. The electrical conductivity that nanomaterials impart to fabrics also improves the functional properties of fabrics. In this way, the durability of the products is increased. Nanotechnological additives include carbon nanotubes and conductive polymers. Carbon nanotubes can significantly improve the electrical conductivity of fabrics, and can effectively dissipate static electricity. Conductive polymers such as polypyrrole, and polyaniline can similarly provide high conductivity in fabrics. However, these materials are susceptible to abrasion, and oxidation [96], [98]. Therefore, the biggest challenge in the use of these materials is the limited lifetime of the materials. In addition, the high cost of these nanomaterials limits their economic use. However, bicomponent fibers and metal fibers are also used to provide antistatic properties. While bicomponent fibers are obtained by combining conductive, and polymer materials, fabrics made with metal fibers offer more robust antistatic properties. However, the use of metal fibers in fabrics can lead to excessive weight gain. Antistatic fabrics produced using nanotechnology are extremely important not only for daily use but also for areas that require high security. These fabrics have potential applications such as electromagnetic shielding, radar wave absorption, and infrared camouflage while enhancing security in areas such as the electronics industry, medical equipment manufacturers, and military personnel. These features offer great advantages, especially for the security, and defense industries [99], [100].

5.3.6. Self-cleaning feature

Nanotechnology is inspired by nature to give fabrics self-cleaning properties. Nanomaterials mimic the micro-, and nano-level structure of the lotus leaf found in nature, making surfaces super hydrophobic [101], [102]. Water and dirt particles cannot adhere to such surfaces, and they can be easily cleaned with a simple stream of water [103], [104]. Textiles with improved self-cleaning properties using nanomaterials show resistance to dirt, and stains as well as antimicrobial, and UV protective properties. These properties are often achieved by applying nanoscale materials such as TiO_2, ZnO, and Ag nanoparticles to the fabric surface [88]. TiO_2 has a photocatalytic effect, breaking down organic impurities, and microorganisms under sunlight [87], [101], [105]. However, TiO_2 nanomaterial has a corrosion effect on textile products. To prevent the corrosion effect of TiO_2 nanomaterial on fabrics, binders such as SiO_2 or acrylic polymers are generally used [106]. These binders ensure that the nanoparticles hold firmly on the applied surfaces, and reduce their release into the environment. Self-cleaning surfaces are based on two principles: super hydrophobicity, and photocatalytic activity. Super hydrophobic surfaces have a water contact angle of more than 150 degrees, and allow water to roll over the surface, and remove dirt [83], [102]. Photocatalytic layers convert organic impurities into carbon dioxide, and water under sunlight [101], [107]. This feature plays a major role in the textile sector, especially in the sportswear industry [88].

5.3.7. Wrinkle prevention

Textiles developed using nanotechnology provide a high level of wrinkle resistance compared to conventional fabrics. At the same time, thanks to the fabrics produced using this innovative technology; the clothes do not wrinkle during use, eliminating the use of ironing. This provides a great advantage for users [104]. In conventional methods, resin is applied to the fabrics used in textile products to give wrinkle resistance. However, such processes cause a decrease in important properties of fabrics such as tensile resistance, abrasion resistance, water absorbency, breathability, and dyeability. TiO_2 and nano-silica nanomaterials are used in textile products to prevent such negative effects [82],[88], [93]. These nanomaterials used in fabrics prevent wrinkles in fabrics by providing wrinkle resistance when applied to yarns. TiO_2 nanomaterial improves wrinkle resistance by forming cross-links between cellulose molecules, and acidic groups under UV rays [86],[93]. Similarly, nano silica material is used in combination with maleic anhydride to significantly improve the wrinkle resistance of yarns [91],[93]. In addition, wrinkle resistance in fabrics can be increased by using various nano-engineering methods. These methods enable the removal of toxic substances from fabrics while maintaining their comfort properties [108]. Nano silica and TiO_2 nanoparticles also offer durability, and environmentally friendly properties when applied to fabrics.

5.4. Environmental impact, sustainability, and future trends of nanotechnology in the textile industry

Nanotechnology is a promising technology that has revolutionized materials science, and improved innovative products such as polymers, and textiles. While this innovative technology has the potential for great advances in technical textiles, the commercialization of nanotechnology-based textiles requires caution [90]. While nanotechnology has come a long way in the improvement and development of textile products, environmental factors should also be taken into account in this process. In addition, ensuring the sustainability of nanotechnology in textile applications is of great importance. Concerns such as ecological footprints in nanomaterials produced with nanotechnology, ecological footprints in the release of nanoparticles during their lifetime, and disposal, environmentally friendly production techniques, and energy-efficient construction stages need to be focused on. Combinations of naturally degradable polymers and reproducible, recyclable materials benefit eco-friendly applications of nanotechnology. Cellulose, silica, or clay-based nanomaterials, which are naturally degradable, and non-toxic, minimize the ecological footprint by providing functions such as waterproof properties, antibacterial properties, wrinkle resistance, UV protection, antistatic properties, and self-cleaning properties in fabrics. Such developments contribute to the sustainability goals of the textile industry by meeting the demands for environmentally friendly textile products [104]. At the same time, the application of nanotechnology in textiles has the power to transform technical textiles in the future.

6. Nanotechnology in food industry

6.1. Food industry

As you know, one of the most basic needs of humans is nutrition. The human body needs carbohydrates, fats, vitamins, minerals, and water to meet basic needs. The industrial sector that provides plant, and animal content, and transforms it into food products that can be stored for a long time, and ready to use after being subjected to many processes is known as the food sector [109]. The industrial sector that provides plant, and animal content, and transforms it into food products that can be stored for a long time, and ready to use after being subjected to many processes is called the food sector [109]. Nanotechnology is spreading rapidly in every field. Although nanotechnology in the food sector has worried people in terms of toxicology, it has been preferred a lot in recent years thanks to its advantages [110]. In the food sector, nanotechnology provides advantages not only for food but also for packaging.

6.2. Applications of nanotechnology in food

There are many different uses of nanotechnology in the food industry, from nanocapsules to nanosensors, from smart packaging to antimicrobial packaging. The packaging stage of food is very important for food preservation. Food packaging is used to prevent bacterial growth in foods and to extend the shelf life of foods. At the same time, food packaging reduces the risk of contamination in foods by keeping foods away from air, light, and bad odors [111]. Nanotechnology has various benefits such as protecting the content of foods in the packaging in the food sector, extending the shelf life of foods, and increasing the nutrient content, and flavor quality of foods [112]. Recently, nanocomposites produced with nanoparticles are available in the food packaging sector. These nanocomposites produced with nanoparticles are of great interest [111]. While food packaging aims to preserve food and reduce the risk of contamination, it offers many advantages when combined with nanotechnology. In the food sector, nanotechnology aims to preserve foods without spoiling with its temperature stability, barrier properties, and environmentally friendly structure [113]. Nanomaterials come into play to use nanotechnology in the food sector. Nanomaterials are used in active, smart, biologically based, and improved packaging systems [113]. This improves the quality of packaging in the food sector. Nanotechnology is also used to improve the robustness, antibacterial properties, and gas permeability of food packaging [111]. Packaging properties such as temperature, gas barriers, and humidity are to be improved. For this, nanocomposites are created by combinations of polymers, and nanofillers [113]. Thanks to nanotechnology, techniques such as nano-coating, nano-lamination, and nano clay are used in the food industry [111]. These techniques improve the performance of food packaging. For this reason, nanomaterials are very important for the food sector. Based on the use of nanomaterials, packaging includes four types of systems: active packaging, smart packaging, bio-based packaging, and enhanced packaging (Figure 7) [113].

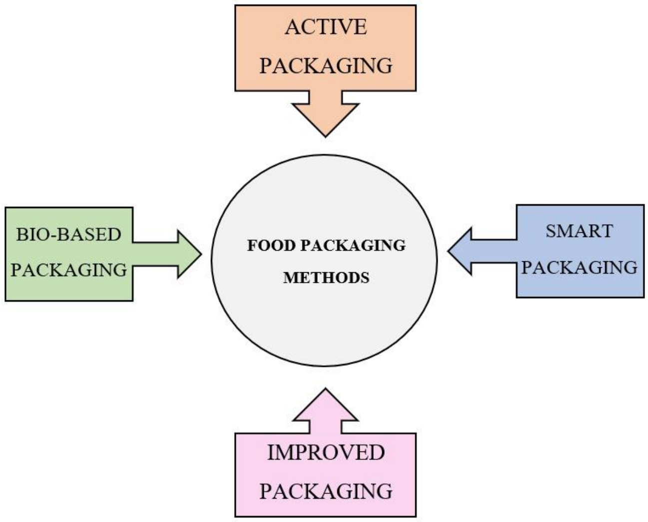

Fig. 7. Types of nanotechnology packaging in the food industry.

6.2.1. Active packaging

It is a method developed in response to continuous changes in consumer dem, and market trends. Active packaging is an innovative food packaging method in line with these requirements [114]. Active packaging has advantages over conventional packaging. The active packaging system provides moisture control and protects the quality of food in contact with air against physical, and chemical degradation (Figure 8) [113]. In this way, it extends the shelf life of the product [115]. In the active packaging system, various additives are added to the packaging. These additives have properties such as oxygen scavengers, ethylene absorbers, microbial inhibitors, and oxidation inhibitors [113],[116]. Deoxidizers absorb oxygen from the packaging and reduce the oxygen level in the packaged food. In this way, food can be preserved for longer than conventional packaging [113], [116]. Ethylene is a phytohormone that is naturally produced in plants and accelerates ripening. When this hormone is overused, the shelf life of foods can be shortened. As a result, properties such as taste, smell, and texture are lost, and the visual appearance of the food deteriorates. For this reason, ethylene absorbers are used. Potassium permanganate embedded in silica gel is the most common ethylene absorber [116]. In addition, chitosan-TiO_2-based nanocomposites are among the new inventions in ethylene scavengers [117]. This invention also provides antibacterial properties to food packaging.

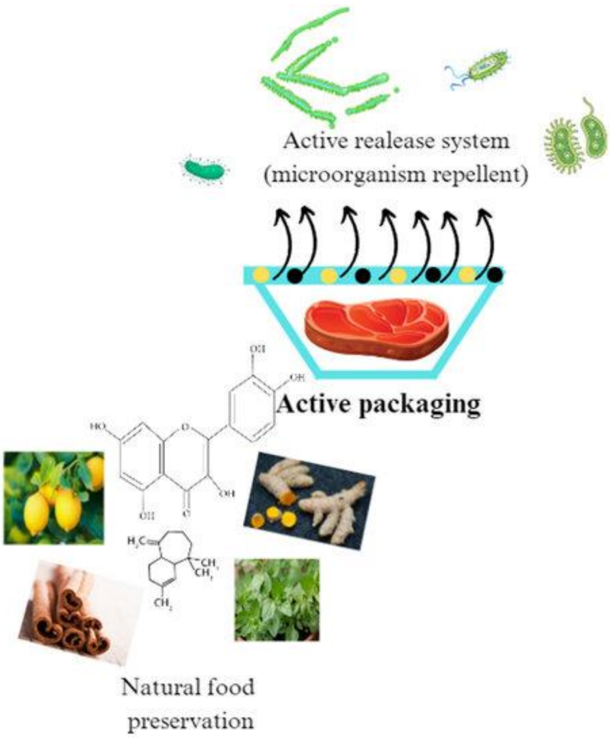

Fig. 8. Active packaging system [118]. Reprinted by permission from MDPI.

6.2.2. Smart packaging

Smart packaging is a new technique used for a specific purpose. At the same time, this nano-technique is a way to monitor changes taking place both inside, and outside the food [111]. With smart packaging, the quality of the products can be monitored with the help of sensors, and the product can be tracked with some labels, barcodes, and indicators [119]. This system increases reliability by providing information to both the producer and the consumer. There are certain factors that contribute to food spoilage. Nano sensors are used to detect these deterioration [113]. These nano sensors can identify allergy-causing proteins, spoiled product content, and harmful microorganisms in food. Nano-biosensors are used to monitor the freshness of food, to determine how many days food should be consumed, and to detect harmful microorganisms in food. Thanks to this packaging system, the consumer can be informed about the entire production, and distribution process. In addition, the consumer can change the color of the packaging thanks to thermochromic ink on the packaging [111].

6.2.3. Bio-based packaging

Reduced waste generation in food packaging has recently attracted a lot of attention. The bio-based packaging industry is showing significant growth in this area [120]. Bio-based packaging provides environmentally friendly, biodegradable packaging with low health hazards, and minimal waste [113]. Thanks to these innovative applications, the food packaging sector opens the door to trade [120]. Bio-based packaging is evolving thanks to bio-based materials. Biodegradable, and bio-renewable materials are becoming sustainable for future generations[113], [120]. Biodegradable materials are the best choice in a biobased packaging system. However, biodegradable materials need to be developed [121]. These synthetic, and non-synthetic polymers are used in the biobased packaging industry. Polylactic acid (PLA), polyethylene furoate (PEF), and polybutylene succinate (PBS) are used as synthetic biobased materials, while polyhydroxyalkanoate (PHA), cellulose, starch, protein, lipids, and waxes are used as non-synthetic biobased materials (Figure 9) [122]. Bio-based packaging can be developed for its sustainable, environmentally friendly, and innovative properties. However, these applications are limited, and insufficient in the long term.

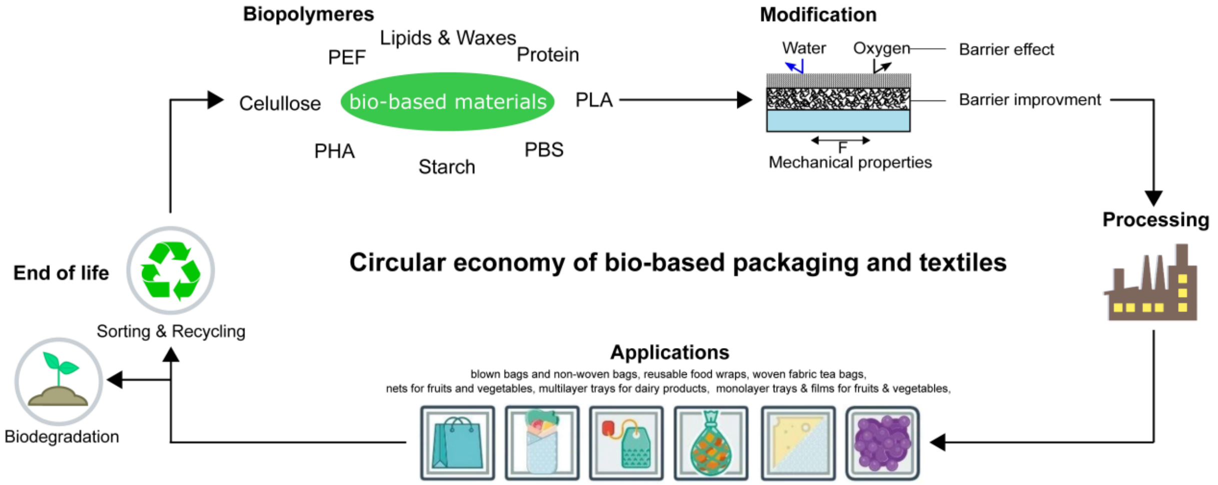

Fig. 9. Illustration of some synthetic, and non-synthetic polymers used in biobased packaging [122], Reprinted by permission from MDPI.

6.2.4. Enhanced packaging

It is an innovative type of packaging that adds properties to food packaging by incorporating nanoparticles. Thanks to these nanoparticles, properties such as long-term preservation, resistance to thermal heat, moisture absorption, UV radiation, and environmental friendliness are added to the packaging [123]. Carbon nanotubes, silver nanoparticles, ZnO (zinc oxide) nanoparticles, and TiO_2 (titanium dioxide) nanoparticles have various benefits in food packaging. Carbon nanotubes are used to provide oxygen sensor structure, provide antibacterial properties, and detect food freshness deterioration [124]. Silver nanoparticles are used for long-term preservation and antibacterial properties of food. Silver nanoparticles show resistance against gram-negative bacteria such as E. Coli, and gram-positive bacteria such as S. Aureus [125]. Ag (silver) nanoparticles are also used in synthetic, and non-synthetic polymers for their antibacterial properties [126]. ZnO (Zinc oxide) nanoparticles show antibacterial properties against bacteria such as E. Coli, and S. Aureus. When ZnO (Zinc oxide) nanoparticles are added to polymers, they form a barrier in composites and improve their antibacterial, and mechanical properties [123]. TiO_2 (Titanium dioxide) nanoparticles are widely used in the food industry and have different applications [123]. Used in food packaging to block UV rays. In addition, TiO_2 (Titanium dioxide) nanoparticles show antibacterial properties like ZnO (Zinc oxide) nanoparticles. TiO_2 (Titanium dioxide) stands out with its harmlessness to health, and its environmentally friendly properties, and therefore shows a photocatalytic effect [126].

6.3. Advantages and disadvantages of nanotechnology in the food industry

Nanotechnology is an increasingly developing field that is gaining importance in technological and economic terms. When this field comes together with the food industry, food packaging with environmentally friendly, low toxic effects and many features emerge. However, these products have both advantages and disadvantages.

6.3.1. Advantages

There are many advantages in the studies carried out in the food industry. Thanks to nanotechnology, the deterioration of the structure of foods is delayed. In this way, foods can be preserved longer. Studies preserve the contents, and flavours of foods. Therefore, healthier, and tastier foods are offered to consumers. In addition, thanks to nanotechnology in food packaging, foods are protected from environmental factors, and the risk of contamination in foods is reduced. Thanks to active packaging, moisture control is ensured in foods, and the quality of food is preserved. Smart packaging detects harmful microorganisms in foods and provides information about how long the food should be consumed. It is also a more reliable packaging model for the consumer. Because it provides information to the consumer from the production to the distribution process. Bio-based packaging is a type of packaging with minimal waste release and environmentally sensitive packaging. In this way, it has a low health impact and is a sustainable packaging method for future generations. Improved packaging protects the packaging, and food from harmful rays thanks to nanomaterials, and provides antibacterial properties. Thanks to these features, it gives confidence to the consumer. In general, it provides satisfaction to the producer, and consumer due to the durability, and performance improvement of the packaging. Thanks to various nanomaterials, it protects from harmful rays with antibacterial properties, and photocatalytic effect. Thus, the confidence of the consumer is gained thanks to the nanomaterials applied. In addition, these nanomaterials are also environmentally friendly thanks to low waste production. Nanotechnology in the food industry has many beneficial effects on the producer, consumer, and the environment.

6.3.2. *Disadvantages*

There are studies in the food industry. However, it raises health concerns for consumers. Nanomaterials used in food packaging can lead to the introduction of human physiology [127]. This can occur due to the contamination of nanocomposites from packages or sensors to food products through air, contact, and ingestion, and the accumulation of packages, and nano sensors in waste piles that can contaminate air, soil, environment, and water. Studies have shown that nanoparticles used in food packaging have serious effects on human health. For example, it is observed that ZnO (zinc oxide) nanoparticles cause changes in cell structure, DNA damage, and disruption in liver cells. In addition, ZnO (zinc oxide) nanoparticles affect genetic material through DNA damage [128]. TiO_2 (Titanium dioxide) nanoparticles are chemically inert. However, studies have shown that it has some toxic effects in experimental animals [128]. At the same time, Ag (Silver) nanoparticles migrate from nanocomposites to foodstuffs, and this migration occurs mostly in acidic foods [127]. Nanomaterials can pass from packaging to food due to problems such as damage, and dissolution of food packaging. In addition, nanomaterials that pass into food packaging raise concerns about environmental damage and human health. [129]. For this reason, the toxic effects of nanomaterials used in food packaging, environmental friendliness, and human health should be taken into consideration.

7. Conclusion

In conclusion, this article has discussed in detail nanotechnological advances in textiles, food packaging, environment, medicine, and energy, and highlighted the societal benefits of applications in these fields. Nanotechnology has become one of the most innovative technological fields of the era with the capacity to respond to the growing, and diversifying needs of societies. The development and use of nanomaterials are leading to both scientific and industrial innovations. In healthcare, medical devices, drug delivery systems, early diagnosis methods, and innovative surgical techniques developed with nanotechnology are revolutionizing treatment and patient care. In

environmental applications, nanotechnology plays a critical role in sustainable agriculture techniques, water purification systems, carbon capture, and pollution reduction. At the same time, biodegradable nanomaterials, and waste management reduce environmental impacts. In the energy sector, nanotechnology contributes to the development of renewable energy technologies while improving energy efficiency. This technology offers innovations in energy storage, and conversion systems while increasing the flexibility of electricity grids. In addition, nanomaterials used in the textile industry provide fabrics with properties such as water repellence, antibacterial, antistatic, self-cleaning, and wrinkle resistance, while in the food industry; nanomaterials add value to the industry by providing active, smart, enhanced, and bio-based packaging solutions.
This review aims to guide researchers working in this field by analysing the status, and potential of nanotechnology in detail. The potential of nanotechnology to shape a sustainable future and provide innovative solutions in various sectors is emphasized.

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The authors dedicated this publication to the 101st anniversary of the Republic of Türkiye. As scientists raised by Türkiye, they are proud to be citizens of this country.

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