Environmental Applications of Nanotechnology: A Review

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Abstract: ***Nanotechnology is an incipient technology for scientific development and holds a great potential for the continued improvement of environmental protection technologies. Environmental problems such as air pollution, water pollution and excessive consumption of natural resources are some of the formidable challenges faced by the communities globally. Application of nanotechnology is receiving more attention on environmental protection and is being applied in the areas of water treatment, wastewater treatment, groundwater remediation, soil remediation and waste management, etc. The volume of nanomaterials and nanoproducts has been anticipated to grow dramatically in the near future and the effective management of nano-waste is of great concern. "This paper reviews the application of nanomaterials for addressing environmental problems." It also highlights the challenges and priorities for responsible management of nano-waste. From the literature analysis, it can be inferred that the technologies like nano zero valent ion, titanium dioxide, carbon nanotubes and metallic nanoparticles are greatly implemented across diverse areas of the environment. It is surmised that there exists a need for the development of adequate regulatory policy on the management of nanomaterial risk. Further, research needs to be conducted to study the life cycle of the nanomaterials and their impact on health and environment.***

Keywords: Nanotechnology, nanomaterials, nano-waste, environment

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1 Introduction

One of the greatest challenges facing the world today is providing better living conditions to people while minimising the impact of human activities on Earth's ecosystems and global environment. In the aurora of the anticipated era of nanotechnology, along with many other nano-technological inventions and breakthroughs in the chemical, medical, electronic, computer, automotive and food industries, there are certainly several examples of environmental applications of nanotechnology and nanomaterials in an effort to utilize nanotechnology as a tool to improve the environment [1]. The development of nanotechnology and its applications extended beyond the original concept of pollution prevention, green engineering presents more defined approaches and is currently considered a crucial component for achieving sustainability [2].

Nanotechnology is widely considered as one of the most promising areas of scientific development for future decades [3]. The rapid evolution of nanoscience and nanotechnology during the past two decades has demonstrated that nanotechnology holds the keys to many of the technological advancements of the 21st century in different sectors (pharmaceutical, electronic, energy, textile, coatings and paintings) which relies on having novel materials with unique properties derived from their small size [4]. Nanotechnology is used in hundreds of products across various industries such as electronics, healthcare, chemicals, cosmetics, materials, and energy [5]. Nanotechnology completely fuses disciplines as diverse as physics, chemistry, materials science, biology, medicine, cognitive sciences, informatics, engineering, computer simulation, industry, agriculture, environmental sciences, etc. [6]. Nanotechnology offers potential economic, societal and environmental benefits [7].

Nanotechnology is expected to enable new technological approaches that reduce the environmental footprints of existing technologies in industrialised countries or to allow developing countries to harness nanotechnology to address some of their most pressing needs [8]. The development of nanoscience and nanotechnology is expected to play an important role for the remediation of environmental problems. One of the ultimate goals of nanoscience and nanotechnology for environmental application is to develop simple and economical routes for designing novel nanomaterials which can efficiently remove various contaminants in the environment and can be easily recovered and reused for many times. A variety of nanomaterials has been adopted for the treatment of pollutants in the environment. For instance, semiconductor nanomaterials that are activated by light, such as titanium dioxide (TiO_2) and zinc sulphide (ZnS), have been utilised to remove organic contaminants from various contaminated sources [9]. Nanotechnology also has the potential to help reduce the human footprint on the environment by providing solutions for energy consumption, pollution and green gas emissions [7].

2 Overview of Nanotechnologies and Nanomaterials used in Environmental Sphere

Many technologies for environmental applications exist in the literature like nano zero-valent particles, silver nanoparticles, carbon nanotubes, bimetallic nanoparticles, titanium dioxide, nanocomposites, magnetic nanoparticles, quantum dots, chitosan, nanocatalyst and ceria. These technologies are useful for environmental applications like wastewater treatment, water treatment, groundwater remediation, soil remediation, waste management etc. Selected nanotechnologies are described below.

1. Nano zero-valent particle - The mechanism of zero valent iron involves a chemical reduction in which contaminants are adsorbed. For the removal of organic contaminants, it involves reductive degradation of chemical i.e. it is destroyed physically. In heavy metals and radionucleotides, it occurs through immobilisation. The contaminants are trapped in physical state [10].

2. Carbon nanotubes - Carbon nanotubes (CNTs) have aroused widespread attention as a new type of adsorbents due to their outstanding ability for the removal of various inorganic and organic pollutants, and radionuclides from large volumes of wastewater. Due to strong Vander waals force of attraction, carbon nanotubes usually adhere to each other to form bundles. This creates adsorption sites and contributes to adsorption. The mechanism of heavy metal ion adsorption involves physical adsorption, electrostatic attraction, precipitation and chemical interaction between the heavy metal ions and the surface functional group. The surface functional group is an important one. The removal of radionucleotide involves strong surface complexation or chemisorption [11].

3. Titanium dioxide - The photocatalytic oxidation, the photoreduction process involves metal ions being reduced to elemental metal deposits on the surface of TiO_2. The deposited metal is recovered or used as the second catalyst in the photocatalytic oxidation, the photoreduction process involves metal ions being reduced to elemental metal deposits on the surface of TiO_2 [12].

4. Bimetallic nanoparticles - Laboratory investigation in the past few years indicated that granular iron could degrade many halogenated organic compounds (HOCs). Some other metals, especially zinc and tin, can transform HOCs quicker than iron. Palladium, with its superior catalytic ability produced spectacular results as well. Ni (II) catalyst could prevent the formation of toxic by-products by dehalogenation of chlorinated compounds via hydrogen reduction rather than electron transfer. Another synthetic bimetallic nanoparticle is Pd/Au, which reduced the chlorinated compounds from water and ground water [13].

5. Silver nanoparticles - The mechanism is related to small size and high surface/volume ratio of silver nanoparticles. Silver nanoparticles can be sorbed to biofilm matrix, indicating a potential role for biological removal of nanoparticles from wastewater. Sorption and accumulation in microbial aggregates may increase the concentration of engineered nanoparticles in biological treatment systems and thus pose a significant threat [14].

3 Review of Nanotechnologies and Nanomaterials used for Environmental Applications

Nanotechnology plays a major role in the development of innovative methods to produce new products, to substitute existing production equipment and to reformulate new materials and chemicals with improved performance resulting in less consumption of energy and materials and reduced harm to the environment as well as environmental remediation [13].

Nanotechnology options under discussion for water treatment include nanomembranes, zeolites or nanoporous polymers for water purification and desalination etc. [15], nanoscale sensor elements for the detection of contaminants and pathogens in water, filters and nanomembranes and magnetic or catalytic nanoparticles for the treatment of wastewater or water remediation [16]. Nanoscience and nanoengineering can provide cost-effective options to restore contaminated groundwater [17]. Nanoparticles could improve the efficiency of catalytic converters in cars and reduce their specific emissions. The remediation of soil at contaminated sites could be facilitated by using iron nanoparticles, a procedure that exceeds conventional methods in efficiency and speed [8].

A comprehensive review of the application of different types of nanotechnologies and nanomaterials to water treatment, wastewater treatment, groundwater remediation, waste management, air and soil remediation has been studied and presented in Table 1. The nanotechnologies and nanomaterials studied include nano zero valent ion, titanium dioxide, carbon nanotubes, bimetallic nanoparticles, quantum dots, ceria, nano-catalyst, etc.

TABLE 1: REVIEW OF NANOTECHNOLOGIES AND NANOMATERIALS USED IN ENVIRONMENTAL APPLICATIONS

Treatment	Nanomaterial	Findings/Result	Auth-ors
Water	Nano-Silver ion (n-Ag)	Silver ions are photoactive in the presence of UV-A and UV-C irradiation, leading to enhanced UV inactivation of bacteria and viruses	[18]
	Titanium dioxide (TiO_2)	Activated by UV-A irradiation, the photocatalytic properties of TiO_2 have been utilised in environmental applications to remove contaminants from water. The strong absorbance of UV-A renders activation of TiO_2 under solar irradiation, significantly enhancing solar disinfection.	[18]
	Chitosan	Used in full-scale water treatment systems as a coagulant/flocculant. Nano-scale chitosan has potential drinking water disinfection applications as an antimicrobial agent in membranes, sponges, or surface coatings of water storage tanks.	[18]
	Carbon Nanotubes	Exceptional water treatment capabilities and proved to work effectively against both, chemical and biological contaminants	[19]
	Gold and silver nanoparticles	Used in the detection and extraction of endosulfan, an important pesticide in the developing world, from water solutions in sub-ppm concentrations	[20]
	Silver catalyst	Highly efficient in controlling microbes in water	[21]
Wastewater	Ceria	An effective sorbent for the removal of As(V) and Cr(VI)	[9]
	Cellulose–Nanoscale-manganese oxide composite (C–NMOC)	Pb(II) removal from aqueous solutions	[22]
	Silver nanoparticles protected by mercaptosuccinic acid (MSA) and supported on activated alumina	Removal of mercuric ions present in contaminated waters	[23]
	Titanium dioxide (TiO_2)	Industrial scale water purification systems, organic contaminant degradation	[18]

	Palladium-containing nanocatalysts	Detoxification of water by a selective destruction of the Halogenated Organic Compounds (HOCs)	[24]
		Successfully tested for selective hydrodehalogenation of wastewater pollutants at the laboratory scale	[21]
	Nano-alumina	Used for the removal of excess nitrates from water	[25]
	Kaolin modified with Nano-zero valent ion	Removal of Pb(II) from electroplating wastewater and possibly from other heavy metal-containing wastewaters	[26]
	Iron oxide nanoparticles (Fe_3O_4)	Convenient and low-cost methods for removal and recovery of metals from wastewater	[27]
	Zero-valent iron nanoparticles	Efficient remediators of a uranium-containing waste effluent	[10, 28]
Groundwater remediation	Nano-zero valent ion	Promising technology for the remediation of contaminated groundwater	[20, 29, 30]
	Ni/Fe Bimetallic nanoparticles	Good choices for the remediation of contaminated groundwater	[20, 31]
	Emulsified zerovalent nanoparticle	Whole sole for groundwater remediation	[20]
	Carbon nanotubes	Effective tool in remediating contaminated waters	[20]
Waste management	Metal oxide nanoparticles (nano-TiO_2, nano-Al_2O_3, nano-SiO_2 and nano-ZnO)	The effect of metal oxide nanoparticles on anaerobic digestion was investigated by fermentation experiments using waste activated sludge as the substrates. Only nano-ZnO showed inhibitory effect on methane generation, and the influence of nano-ZnO was dosage dependent	[32]
	Silver Nanoparticles	At the concentration of 1 mg/kg solids have minimal impact on landfill anaerobic digestion, but a concentration of 10 mg/kg or higher inhibit methanogenesis and biogas production from Municipal Solid Waste. Supporting evidence includes reduced biogas production, prolonged period of accumulation of Volatile Fatty Acids, acetic acid, soluble Chemical Oxygen Demand, low pH, and decrease in methanogenic population	[33]
Air	Ceria	Acted as a support for gold nanoparticles and exhibited high activity for CO removal by catalytic oxidation with high durability	[9]
	Titanium dioxide (TiO_2)	Used in Room Air Purifier, to remove volatile organic	[18]

		compounds and kill bacteria	
Soil remediation	Nanoscale zero-valent iron	Immobilization strategy to reduce Pb and Zn availability and mobility in polluted soils	[10, 34]
	Nanoscale zerovalent iron and palladized bimetallic particles	Remediation of a trichloroethene (TCE)-contaminated plume within a clayey soil	[35]
	Synthesised nanoscale Fe^0	High potential for the remediation of soils contaminated with hazardous and toxic compounds such as chlorinated organic compounds and nitroaromatic compounds	[36]
	Aluminium lactate modified Nano Iron Particles	Reactivity of bare Nano Iron particles (NIP) with Dinitro Toluene (DNT) increases with increasing NIP dosage. Degradation of DNT was achieved with bare NIP at a lower dosage (4 g/L) but near complete destruction was obtained at a higher dosage (100 g/L). Reactivity was found to increase with increasing reaction time. Although the reactivity was less compared to bare NIP initially, the aluminium lactate modified NIP become as effective as bare NIP with increasing reaction time	[37]
	Iron nanoparticles	Remediate Polychlorinated biphenyl (PCB) contaminated soil and an attempt was made to maximise PCB destruction in each treatment step. It was found that at 300°C in air, iron oxide and V_2O_5/TiO_2 are also good catalysts for remediating PCB contaminated soils	[38]

3.1 Specific implications of nanotechnology for agriculture and food security

Several potential applications of nanotechnology to agriculture and food systems include:

- Disease diagnosis and treatment delivery systems.
- New tools for molecular and cellular breeding.
- Development and modification of new food products (smaller, more uniform particles, heat-resistant chocolate, powder suspension, etc.)
- New food packaging materials and systems.
- To date, a number of significant advances have been made in areas of materials (nanoparticles, nanoemulsions and nanocomposites), food safety and biosecurity (nanosensors and nano-tracers), products (delivery systems and packaging), and processing (nanobiotechnology).

3.2 Specific implications of nanotechnology for water and wastewater management

- There are two major research needs for full-scale applications of nanotechnology in water/wastewater treatment.
- First, the performance of various nanotechnologies in treating real natural and waste waters needs to be tested. Future studies need to be done under more realistic conditions to assess the applicability and

efficiency of different nanotechnologies as well as to validate nanomaterial-enabled sensing technologies.

- Secondly, the long-term efficacy of these nanotechnologies is largely unknown as most lab studies were conducted for a relatively short period of time.
- Also, there is need to bring down the high cost associated with nanotechnological applications.
- A major challenge for water/wastewater treatment is water quality monitoring due to the extremely low concentration of certain contaminants, the lack of fast pathogen detection, as well as the high complexity of the water/wastewater matrices.
- Innovative sensors with high sensitivity and selectivity and fast response are in great need.

3.3 Other environmental applications of nanotechnology and nanomaterials

- Development of novel methods for the synthesis of nanostructured TiO_2 catalyst nanoparticles or immobilised on supports for the solar detoxification of water and air, the preparation and application of nanoscale iron for adsorption and destruction of organic contaminants in water.
- The synthesis of novel nanosized catalysts with high selectivity of the desired product, the fabrication of novel biosensors for probing individual cells and biologically derived substances, nanomaterial-based sensors for monitoring toxins in water and air and environmentally benign nanocomposites in construction, computers and electronic devices.
- Although currently expensive, carbon nanotubes are also considered promising materials for hydrogen storage, an application that will be crucial in the development of efficient hydrogen-based vehicles, which are expected to have minimum atmospheric emissions is desired in near future.

4 Priorities and Challenges to Environmental Applications of Nanotechnology

Though nanotechnology is emerging and has wide applications in the field of environment, it is faced by several challenges that prevent its application on an extensive scale. The challenges include risk to health and environment, the emergence of nano-waste, the high cost of the nanotechnology products, need for legislative measures for effective management of the nanotechnology products, research on nanotoxicity of products, etc. A few challenges are discussed below.

1. Risk to health and environment

The production, use and disposal of products containing nanomaterials may lead to their appearance in the air, water, soil or even organisms [39]. Concerns about potential risks to health and the environment arising from exposure to nanomaterials have led to a general consensus that in order for nanotechnology to reach its full potential, studies must be conducted to understand and control any potential risks [40]. The health risk of a nanoparticle is a function of both its hazard to human health and its exposure potential [5]. Governmental agencies and research organisations are continuously working on the development of analyses and methods to evaluate the risks of manufacturing and using nanomaterials for both health and the general environment [4]. Despite many research initiatives throughout the world, only little is known about the potential environmental and health impacts of nanomaterials and much of the research undertaken so far have raised more questions than answers [39].

Understanding of the environmental effects and risks associated with nanotechnology is very limited and inconsistent [7]. There is significant concern about whether existing test methods, trigger values, and other standard approaches to risk assessment are applicable to nanomaterials given the significant differences in their physical, chemical, and toxicological properties from macro scale substances [41]. It is required to conduct a risk assessment and full life-cycle analysis for nanotechnology products at all stages of products to understand the hazards of nano products and the resultant knowledge that can then be used to predict the possible positive and negative impacts of the nanoscale products [7]. Many of the most important health and safety concerns of engineered nanomaterials and nanotechnologies are due to lack of knowledge of health effects and of levels of occupational and other types of exposure to engineered nanomaterials during the production and use of engineered nanomaterials as well as in applying different engineered nanomaterials in applications of nanotechnologies for consumer and other products [42].

Risk assessment for nanoparticles has to take into account the toxicological hazard, the probability of exposure and the environmental and biological fate, transport, persistence, transformation into the finished product and recycling. The likelihood of exposure can be reduced by encapsulating the nanomaterials within an inert barrier (e.g. silicon can be used to coat quantum dots) or by creating immobile nanostructures on a surface that have a similar activity to free nanoparticles without the risks inherent in dispersion [43]. To identify and reduce hazards it is appropriate to consider the cradle to the grave life cycle of nanomaterials [44]. Life cycle assessment (LCA) exercises are crucial to analyse, evaluate, understands and manage the environmental and health effects of nanotechnology [45].

2. Nano-wastes

Nanopollution is a generic name for all waste generated by nanodevices or during the nanomaterials manufacturing process [46]. One of the side effects of wide utilisation of nanotechnologies is the release of nanomaterials to the environment [47]. Most human-made nanoparticles do not appear in nature, so living organisms may not have appropriate means to deal with nano-waste [46]. Nanotechnology has ushered in a new era of miniaturisation at industrial scale production and this has triggered the emergence of new unique forms of waste streams – containing residue nanomaterials - which potentially may pose challenges to the current waste management practices and technologies. Nano wastes are likely to introduce new challenges of managing waste streams with respect to classification, identification of appropriate handling techniques, and the development of appropriate legislative frameworks to govern them [48].

Many of the current and anticipated uses of nanomaterials (e.g. consumer products and construction materials) have the potential to produce significant sources of nanoparticles into waterways as waste [49]. Separate categories of nano-waste are nanoparticles released in the process of utilisation of nano products, which can lead to pollution of soils, sludges, or sediments. Recycling of nano products will require segregation of used nanoproducts, dismantling of their components, and possible reuse and recovery which could be achieved by chemical or physical methods. Combustion is yet another possibility for waste treatment, applicable in the case of carbon-rich materials disposed of in bulk quantities [47].

Davies (2006) [50] argued that the present legislative framework is unable to deal with nano-waste and may potentially yield unintended consequences to human health and the environment if not amended to take into account the emerging increase of nano-waste streams. Nano wastes classifications have several benefits including isolating waste types that merit special operational management practices during production, handling, transportation, storage, treatment and disposal to mitigate against any form of adverse effects to the humans and the environment due to their degree of hazardousness. Secondly, it allows effective determination of appropriate modes of treating and disposing of various types of nano-waste [48]. Currently, there is no internationally agreed nano-waste classification system or paradigm that can support the waste management industry and regulators in developing precautionary and practical approaches to managing different classes of waste streams containing nanoscale materials and thus Musee in 2011 [48] proposed a five-stage classification for nano-waste:

TABLE 2: FIVE-STAGE CLASSIFICATION FOR NANO-WASTES

Class	Nanomaterial Hazard	Exposure
I	non-toxic	low to high
II	harmful or toxic	low to medium
III	toxic to very toxic	low to medium
IV	toxic to very toxic	medium to high
V	very toxic to extremely toxic	medium to high

Nanomaterials certainly do not behave in the same way as normal waste and therefore standard tests may not be suitable to predict the fate of nanoparticles disposed of in landfills [51]. Further adjustments to the environmental and workplace standards need to be imposed in future. For example, handling nano-waste may require revision of personal protection equipment and work routine. As the nano age is approaching fast, it is important to find organisms that possess a high resistance to nanoparticles and which are able to accumulate, utilise, decompose or immobilise or decompose nanoparticles. Bio utilisation of nanoparticles by microorganisms, fungi and plants may help to clear the environment and protect living organisms [47]. Incorporation of nanomaterials into existing technologies creates the need to revise the existing LCA studies. LCA reports need to be made for different classes of nanoparticles and nanoproducts, so as to predict the real threat of nano-waste. However, at present, it is impossible to obtain a full-spectrum LCA for nanotechnology due to insufficient knowledge about the detailed inputs and outputs of the system [45].

3. Legislative measures

In new technology like nanotechnology, an additional element is also required: public and regulatory acceptance. This is primarily focused on the health and safety of the materials and products including the environmental impact [52]. Governmental policy aimed at hazard reduction regarding nanoparticles has been extremely limited [44]. Development of policies for nanomaterials either by regulatory based or by industrial self-regulatory that includes an industrial commitment to research the potential impacts of their technology are needed [53]. Given the limitations of existing regulatory tools and policies, distinct initiatives in the areas of rapid development and implementation of voluntary standards of care and development of adequate regulatory policies on nanomaterial risk management are urgently needed [54].

The United States, Canada, Australia and Japan continue to follow the traditional model of environmental regulation in regard to nanomaterials while the European Union (EU) prescribes to the precautionary principle. The US and Canada have issued statements that new nanomaterials are considered chemical substances and as such, are subject to the standard regulatory practices under environmental laws. The Organization for Economic Co-operation and Development (OECD) had convened a working group on manufactured nanomaterials to address the specific regulatory questions on nanotechnology [41].

- A comprehensive study of all interdependent factors affecting sustainability and how nanotechnology solutions can extend the limits of sustainable development must be undertaken and updated each year.
- Solar-powered photocatalytic systems and separation systems (e.g., nanoporous membranes with ion-channel mimics) that extract clean water, energy and valuable elements (e.g., nutrients and minerals) from impaired water including wastewater, brackish water and seawater.
- Multifunctional sorbents/membranes that can capture CO_2 from flue gases and transform it into useful products (e.g., chemical feedstocks) must be optimised and then scaled up for industrial scale use.
- Development of more efficient, cost-effective, and environmentally acceptable separation systems (e.g., chelating ligands for solvent extraction, ion-exchange media, and affinity membranes) for recovering critical minerals such as rare earth elements (REE) from mine tailings, leaching/hydrometallurgical solutions and wastewater from mineral/metallurgical extraction and processing plants.
- Green manufacturing technologies to (i) develop nontoxic and cost-effective substitutes for REE and (ii) reduce and (eventually) eliminate the release of toxic pollutants into the environment.
- Comprehensive utilisation of nanotechnology at the present time and unprecedented application of nanoparticles in products will certainly create significant amounts of new-generation-waste in the near future. Future research efforts need to be directed towards finding new methods for nanotoxicology, recognition of biological effects of nanoparticles in the environment, and the creation of the bases of nano biomonitoring.
- It is important to develop an efficient and effective strategy for the recycling and recovery of nanomaterials and methods are needed to assess whether the potential benefits of nanotechnology outweigh the risks.

5 Conclusions

Nanotechnology is an emerging science and has widespread applications in diverse areas. For the nanotechnology to succeed on a large scale, it needs to overcome several challenges that it poses. The review indicates that nano zero valent ion, titanium dioxide, metallic nanoparticles and carbon nanotubes are the nanotechnologies which are widely applied in the areas of water treatment, wastewater treatment, groundwater remediation, soil remediation, waste management, etc.

Nanotechnology appears as a positive solution for the current environmental problems. The challenges of nano-waste, the risk to health and environment and the regulatory approach could possibly overcome after further research in this field. There is a need for extensive research in this field to overcome the challenges of risks to health and environment, management of nano-waste and LCA of the nanomaterials. The large scale research in nanotechnology is limited to few countries like USA, UK, China, etc. and hence there is a need for countries to collaborate and work on the challenges faced globally in this field. A collaboration of research centres, industrialists, policy makers and government regulators is needed for this technology to flourish in the coming decades. Proper R&D, education on nanotechnology and green engineering, along with new and innovative ideas, judicious decisions, ethical responsibility, and proper risk-assessment strategies, will certainly assist in utilising the potential of nanotechnology and nanomaterials to improve life on Earth while minimising environmental impacts. However, it would be interesting and important to examine and scrutinise any potential negative environmental and health implications of nanotechnology and nanomaterials. Very few life cycle studies on nanotechnology have been conducted. A thorough LCA approach is needed to study the effect of various nanotechnologies on health and environment. Further, following the principles of green engineering to perform cradle-to-cradle design of nanomaterials and nanodevices will certainly enhance the beneficial implications of nanotechnology. It is also important to be able to implement nanotechnology with minimal changes to existing infrastructure in the near future.

As nanotechnology continues to advance, there is an growing focus on addressing two key questions related to sustainability over the coming decades:

1. How can nanotechnology help address the challenges and provide opportunities of improving local and global sustainability?
2. Can nanotechnology be developed in a sustainable fashion?

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