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Nanomaterials in Geoscience: Emerging Model for Sustainable Earth Systems

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Abstract:
The field of geoscience has witnessed the advent of nanomaterial technology that holds promise as revolutionary tools in the fields of environmental management, resources recovery, energy efficiency, and climate change mitigation. Due to their unusual physical and chemical properties, such as high surface area, enhanced reactivity, and controllable structures, nanomaterials have seen applications in areas like groundwater remediation, mining exploration, geotechnical engineering, carbon sequestration, environmental monitoring, and enhanced resource recovery. In this article, we present an overview of the applications, properties, and classification of nanomaterials in geoscience along with the role played by nanomaterials in sustainable earth system management. Some of the key developments have included the application of nanoscale zero-valent iron in degrading contaminants, nano-sensors for environmental assessment, and nanostructures in mineral separation and energy recovery. However, there are some major obstacles, like nanoparticle toxicity, environmental persistence, economics, and regulation, in large scale application of these nanomaterials. Considering the inherent complications and uncertainties of the sustainability impact assessment process, the current study introduces a fuzzy logic-driven framework. In the introduced model, important parameters, such as resource exploration efficiency, remediation potential, carbon capture efficiency, energy optimization, and ecological risk mitigation, have been considered in determining the Sustainability Impact Index (SII). With the use of fuzzy inference system, the suggested framework will help in making decisions amid uncertainties and changing environmental conditions. The introduced framework is an effective way of assessing the sustainability performance of nanomaterial usage in the field of geoscience through the use of proper resource management and environmental protection.

Keywords: *Nanomaterials, Geoscience, Sustainable Earth Systems, Fuzzy Logic, Environmental Remediation, Carbon Capture, Resource Exploration, Sustainability Impact Index (SII).*

1. INTRODUCTION

It is during the 21st century that a novel fusion of materials science and geoscience towards sustainability has been achieved. With increasing pressure on the earth systems due to factors such as global warming, resource shortages, contamination of ground water resources, and environmental degradation, there arises a need for developing innovative techniques that can ensure balance between man and nature. One such technique that has found its way into the geoscience arena after having been used extensively in the field of physics and material science is nanotechnology, characterized by its distinctive abilities at the atomic and molecular levels (Zhang, 2003). The application scope is immense for geoscientists in many forms such as soil decontamination of heavy metals and organic compounds, better methods of geochemical sensing and monitoring, new approaches to mineral extraction, stabilization of loose soil, and improved techniques of carbon capture and sequestration. All these developments will be especially useful in developing nations such as India due to its rapid industrial growth causing an immediate demand for sustainable techniques (Singh & Misra, 2015).

Nanomaterials have recently become innovative materials in geoscience owing to their unique physicochemical characteristics which allow advanced applications in mineral exploration, environmental clean-up, carbon sequestration, and sustainable management of resources. The evaluation of the sustainability impact of nanomaterials requires considering several interconnected factors and uncertainties. In order to address these problems, fuzzy logic offers an effective tool for making decisions which combines various geoscience parameters into a single decision-making framework. A fuzzy model evaluates the sustainability performance of nanomaterial applications in Earth systems using the Sustainability Impact Index (SII) (Zadeh, 1965; Ross, 2010). The objectives of the present paper include: (i) classification and description of the key characteristics of nanomaterials from a geoscience point of view, (ii) assessment of applications of nanomaterials in different geoscience disciplines, and (iii) analysis of problems associated with sustainable integration of nanomaterials. Through the synthesis of existing knowledge, the paper shows how nanotechnology can assist in attaining sustainable Earth system.

2. NANOMATERIALS: CLASSIFICATION AND PROPERTIES

Nanomaterials can be broadly classified into four categories:

1. **Carbon-based nanomaterials** – including carbon nanotubes (CNTs), graphene, and fullerenes, notable for their high tensile strength, conductivity, and adsorption capacity.
2. **Metal and metal-oxide nanoparticles** – such as iron, titanium dioxide, and zinc oxide, widely applied in remediation, photocatalysis, and geotechnical stabilization.
3. **Polymeric nanomaterials** – engineered for controlled release of reactive agents or additives in soils and aquifers.
4. **Composite nanomaterials** – hybrids combining multiple nanoscale components to optimize multifunctional properties (Nowack & Bucheli, 2007).

Nanomaterials are known to exhibit distinct physicochemical properties, which give them great utility in numerous fields of geosciences and environmental studies. Among their key properties is an extremely high surface-area-to-volume ratio, which is much higher than that of common bulk materials. Increased surface area increases their reactivity and speeds up reaction kinetics, thus increasing their effectiveness in environmental cleaning and geochemical reactions (Klaine et al., 2008). Nanomaterials also demonstrate quantum confinement at the nanometer scale and have unique optical, electrical, and magnetic properties that are not displayed by bigger particles. These properties play a big role in creating advanced sensors for geological surveys and environmental monitoring.

One of the significant characteristics of nanomaterials is their high adsorption capacity.

Because of the availability of many active surface areas, the nanomaterials are capable of adsorbing different pollutants such as toxic heavy metals and organic substances. For this reason, nanomaterials have been widely used in the purification of water, soil cleaning, and various types of waste treatment (Roco, 2011). Also, a number of metal oxide nanomaterials possess very good catalytic capacity, allowing them to participate in photochemical and reduction reactions aimed at the destruction of pollutants and geochemical compounds transformation. The above-mentioned characteristic improves the efficiency of sustainable environmental management techniques. Therefore, the knowledge of these basic characteristics of nanomaterials is vital for designing and improving nanomaterials for specific geoscientific problems.

3. APPLICATIONS OF NANOMATERIALS IN GEOSCIENCE

Nanomaterials have become transformative instruments in geoscience owing to their distinctive physicochemical characteristics such as high surface area, increased reactivity, and improved adsorption. The uses of these materials are many and varied in geological and environmental research, providing important contributions towards sustainable resource management and environmental conservation. Nanomaterials find applications in mineral exploration by acting as highly sensitive detectors for trace elements, rare earth elements (REEs), and mineral deposits beneath the earth's surface (Hochella et al., 2008). Nanomaterials are also significant in geochemical analysis through improved elemental and isotope analysis (Handy et al., 2008). As far as environmental geoscience is concerned, nanomaterials are widely used for groundwater and soil cleanup. It has been established that iron-based nanomaterials, especially nanoscale zero-valent iron (nZVI), show high efficacy in the removal of heavy metals, radionuclides, and organic contaminants from contaminated sites (Karn et al., 2009). Additionally, nanotechnology contributes to carbon capture and storage (CCS) projects through increasing carbon dioxide absorption in geological formations (Lalley et al., 2016). Nanomaterials have also been extensively used in petroleum and reservoir engineering. Enhanced oil recovery through increased mobility, lowered interfacial tensions, and reservoir wettability changes is achieved through the use of nanofluids (Sun et al., 2017). Furthermore, the use of nanomaterials in geosciences involves their use in the formulation of durable drilling fluids and the development of efficient subsurface monitoring technology. With respect to geomaterials science, the study at the nanoscale has helped greatly in understanding the weathering processes of minerals, rock-fluid interactions, and mechanics of geological materials (Hochella et al., 2019). The continued evolution of nanotechnology has led to its application in various aspects of geosciences.

3.1 Groundwater and Soil Remediation

The pollution of underground water and soil is one of the major issues of the environment in the world. Zero valent iron nanoparticles (nZVI) have been widely investigated for the treatment of chlorinated hydrocarbons, arsenic, and nitrate contamination (Zhang, 2003). Their strong reduction capability helps them in transforming the hazardous chemicals into safer products. Researches show the use of bimetallic nanoparticles (for example, Fe-Pd) to increase the rate of dechlorination of organic substances (Li et al., 2006). Carbon-based nanomaterials like graphene oxide and CNTs have been found to exhibit high adsorption capacity for heavy metals such as lead and cadmium (Das et al., 2016). They are being used in permeable reactive barriers for protecting the aquifers. In agriculture, nano-fertilizers are being tested for reducing the leaching of nutrients from the soil while maintaining its productivity.

3.2 Mineral Exploration and Geochemistry

Nanomaterials are seen as revolutionary instruments for geosciences investigation, especially in the domains of mining and geochemistry. Due to the special physicochemical characteristics of nanomaterials such as high surface area, increased reactivity, and high sensitivity, nanomaterials are now used successfully in geoscientific detection of minerals. Special types of sensors based on the usage of nanotechnology like quantum dots, carbon nanotubes, and nanotechnology-based semiconductors provide the capability of sensing trace amounts of geochemical pathfinder elements with remarkable accuracy. With the help of these sensors, high sensitivity can be achieved in the investigation of commercially significant mineral deposits, including gold, rare earth elements (REEs), and uranium (Hood, 2016). Moreover, nanoparticles are becoming more widely used as tracer tools in hydrogeological and environmental studies. Being very small and having a controlled surface structure, engineered nanoparticles may serve as excellent tools for tracing fluid motion in the subsurface environment, allowing researchers to better understand such phenomena as groundwater flow and the process of contamination transport in the environment. These uses help improve management of groundwater resources and environmental monitoring. In addition, nanomaterials can be used in analysis of geochemical processes, such as dissolution and adsorption of minerals and elements in geological formations.

The integration of nanomaterials into geoscientific research continues to offer innovative solutions for resource assessment, environmental protection, and subsurface characterization, thereby contributing to the development of more accurate and sustainable approaches in earth science studies (Hood, 2016; Klaine et al., 2008). Nanotechnology has enabled the development of high-sensitivity sensors for mineral exploration. Quantum dots and nanostructured sensors can detect trace concentrations of geochemical pathfinders, improving exploration efficiency for gold, rare earth elements, and uranium (Hood, 2016). Nanoparticles are also used as tracers in hydrogeological studies to understand groundwater flow and contaminant migration. However, the application of nanomaterials in geoscience continues to provide new ways of handling the issues of resource evaluation, environmental conservation, and subsurface analysis hence promoting the creation of more precise and sustainable methods of study in earth sciences (Hood, 2016; Klaine et al., 2008). Through nanotechnology, the manufacture of highly sensitive sensors in the identification of minerals for exploration purposes has been made possible. The use of quantum dots and nanosensors is instrumental in identifying traces of geochemical pathfinders hence making exploration of gold, rare earth metals, and uranium more efficient (Hood, 2016).

3.3 Geotechnical Engineering

Nano-clay and silica nanoparticles find applications in geotechnical engineering in the stabilization of weak soils, as well as in the enhancement of the shear strength and reduction of the permeability of such soils (Nazari & Sanjayan, 2015). Examples include improved resistance of nanosilica-grouted tunnels and foundations. The addition of CNTs to cement-based products improves their compressive strength and decreases micro cracks (Sanchez & Sobolev, 2010). Nanomaterials are new materials that have been introduced in geotechnical engineering owing to their outstanding physical, chemical, and surface properties. Nanomaterials have greatly improved the process of soil stabilization, foundation, and durability of civil engineering structures. Nano-clay and silica nanoparticles have proven to be very effective among the various nanomaterials being utilized in improving the engineering properties of problem soils. These nanoparticles make soils strong by increasing the bonding between particles of the soils, increase the shear strength of soils, minimize compressibility, and reduce permeability, thus improving the general ground stability and bearing capacity (Nazari & Sanjayan, 2015).

Silica nanoparticles are also widely used in grouting where nanosilica modified grouts have higher permeability, lower shrinkage, and better durability than standard grouts. These properties lead to improved performance in tunneling, underground works, and foundation strengthening. In addition, there is much interest in using carbon nanotubes (CNTs) in cement and concrete structures due to their geotechnical and construction applications. The unique strength and high elasticity of carbon nanotubes help increase the compressive strength, fracture toughness, and toughness of cement-based materials. They are capable of bridging microcracks and preventing crack propagation that helps to decrease deterioration and prolong the lifetime of geotechnical structures (Sanchez

& Sobolev, 2010). Thus, nanotechnology materials can be considered as sustainable materials that can be used to improve the performance and lifetime of geotechnical systems.

3.4 Climate Change Mitigation: Carbon Capture and Sequestration

The role of nanomaterials in CCS processes has been acknowledged in recent times. This includes metal-organic frameworks (MOFs), mesoporous silica, and zeolite nanoparticles, which provide an advantage of a higher adsorption capacity of CO2 due to their ability to tune the pores (Sumida et al., 2012). Nanomaterials also facilitate the mineral carbonation technique of permanent sequestration of CO2 in the form of carbonates inside geological formations (Wang et al., 2016). The development of novel nanomaterials has played a key role in geoscience research especially in relation to combating climate change via innovative carbon capture and storage (CCS) systems. The rising levels of carbon dioxide (CO2) in the atmosphere as a consequence of human activity have made it extremely important to adopt effective mechanisms of managing carbon in order to mitigate climate change. In this regard, nanoparticle materials such as metal organic framework (MOF), mesoporous silica, carbon nanotubes, and nano zeolites have proven highly effective in the process of CO2 adsorption because of the presence of a high surface area, tunable pore sizes, and selective adsorption ability (Sumida et al., 2012). Moreover, the importance of nanomaterials is apparent in the process of promoting the mineral carbonation method, which is a type of geological carbon sequestration that involves the transformation of captured CO_2 into stable carbonate through reactions with naturally occurring minerals. Nanomaterials expedite this process because they increase the surface area and enhance the efficiency of mass transfer of these minerals, leading to an effective reaction with CO_2 (Wang et al., 2016). This way, carbon is permanently stored within the geological formations without any possibility of escape into the environment. The use of nanotechnology in geological carbon sequestration is a way of improving CCS techniques while promoting global sustainability efforts to address climate change. Therefore, carbon capture technology using nanomaterials is considered promising for attaining carbon neutrality.

3.5 Environmental Monitoring and Sensing

Advanced sensors employing nanomaterials have the ability to monitor the presence of pollutants, changes in pH, and redox potential in groundwater and soil. Nanosensors using CNTs and gold nanoparticles can sense heavy metals at a parts-per-billion level, thus giving early indication about any pollution (Varghese et al., 2001). In geophysical surveys, the use of nanoscale magnetometers increases accuracy in identifying subsurface anomalies. Nanomaterials have come to be seen as game-changing agents for monitoring and sensing purposes in the geosciences field. The unique physical and chemical properties of nanomaterials such as high surface area, increased electrical conductivity, and sensitivity make possible the manufacture of highly effective sensors that can detect environmental changes on a real-time basis. There is an increasing use of sensors based on nanomaterials for the purpose of detecting pollutants, changes in pH and redox conditions, among others, in groundwater, surface water, and soils. Some of the nanomaterials that stand out in terms of their performance in detecting heavy metals and contaminants in trace amounts include carbon nanotubes (CNTs), graphene, and gold nanoparticles (Varghese et al., 2001; Kumar et al., 2022). In addition to this, nanotechnology has greatly advanced geophysical exploration and subsurface investigation techniques. Nanoscale magnetic sensors and magnetometers have been developed which allow better sensitivity and spatial resolution in the identification of small-scale magnetic anomalies linked with the mineral deposits, aquifers, fault lines, and other geological formations. These developments help improve geological surveying and prospecting activities without causing any environmental disturbance. Additionally, the use of nanomaterials in environmental monitoring networks is also aiding in continuous data acquisition. This further improves the risk assessment and sustainable resource management initiatives. Hence, sensing technologies with the aid of nanomaterials are emerging as crucial solutions to current geoscientific and environmental issues (Mao et al., 2019; Kumar et al., 2022).

3.6 Sustainable Mining and Resource Recovery

Moreover, nanotechnology provides avenues for sustainable mineral processing operations. Nanoflotation techniques increase the efficiency of recovering rare earth elements and base metals by minimizing the use of chemicals (Gupta & Banerjee, 2017). Bio-nanotechnological methods that employ microbial-nanoparticle consortiums have been proposed to achieve environmentally friendly gold mining without using cyanide.

The use of nanomaterials as innovative means to promote sustainable mining operations and increase the extraction of resources from primary ores and secondary sources has become evident. Nanomaterials have contributed immensely to the effectiveness of mineral processing techniques by minimizing their environmental impact. For instance, nanoparticle-based flotation methods have proven effective in increasing the selectivity and extraction of valuable minerals such as rare earth elements (REEs) and base metals. Nanoparticles affect mineral surface characteristics in a way that minimizes the need for traditional chemicals, hence decreasing production expenses and pollution (Gupta & Banerjee, 2017).

Alongside with flotation techniques, nanomaterials are currently used in bio-hydrometallurgy to obtain metals in an environmentally friendly manner. The technology of bio-nanotechnology involves the use of microorganism features combined with nanotechnology to recover metals from poor ores or mine wastes. A microbial and nanoparticle consortium has shown great promise in gold processing in terms of metal dissolution and recovery with decreased toxicity levels of chemical compounds like cyanide. The mentioned method is less environmentally hazardous than classical methods of gold processing and contributes to environmentally sustainable mining as well (Gupta & Banerjee, 2017). Overall, the application of nanotechnology in mining and resource recovery supports the principles of sustainable development by improving extraction efficiency, reducing waste generation, conserving natural resources, and minimizing the environmental footprint of mineral processing activities. As research advances, nanomaterial-based technologies are expected to play an increasingly important role in the transition toward environmentally responsible and resource-efficient mining systems.

4. CHALLENGES AND RISKS OF NANOMATERIAL IN GEOSCIENCE

While nanomaterials have the potential for revolutionary use in geoscience applications like remediation of the environment, exploration of minerals, groundwater purification, and geohazards monitoring, there are many challenges that arise along with their increasing use in these applications. One of the major challenges is the possible toxicity of the nanoparticles used. Nanoparticles are very small in size and highly reactive; therefore, when they come in contact with living organisms, they can cause adverse effects in microorganisms, plants, animals, and water bodies (Klaine et al., 2008). Another problem that should be mentioned is the migration of nanoparticles in the environment. Released into the environment, nanoparticles can move through soils, sediments, and groundwater aquifers, contaminating uncontaminated areas before. The further fate of these nanoparticles is also under investigation. The economic issue hinders the use of nanotechnology in geoscience on a grand scale. The development, synthesis, and use of nanomaterials sometimes call for sophisticated technology and high costs that make it difficult for their use in economically disadvantaged regions (Roco, 2011). In addition, the current regulatory regime has been unable to match the pace of technological advancement. Lack of a standard approach for characterizing, assessing risks of, and monitoring nanoparticles raises concerns about their appropriate use and disposal (Maynard, 2014). Thus, while there are great opportunities that nanomaterials offer for geosciences and environmental sustainability, the development and use of nanomaterials should be underpinned by a thorough life cycle analysis and environmental monitoring as well as regulation.

Despite significant promise, the deployment of nanomaterials in geoscience is not without challenges.

1. **Toxicity and environmental risks**: Nanoparticles may exhibit cytotoxic effects on microorganisms, plants, and aquatic systems, raising concerns about unintended ecological consequences (Klaine et al., 2008).
2. **Persistence and mobility**: Nanoparticles can migrate through soils and aquifers, potentially introducing contaminants to previously clean environments (Nowack & Bucheli, 2007).
3. **Economic costs**: Large-scale production and deployment remain costly, limiting their use in low-resource settings (Roco, 2011).
4. **Regulatory frameworks**: Current regulations often lag behind technological advances, creating uncertainty in risk assessment and standardization (Maynard, 2014).

5. FUTURE PROSPECTS AND SUSTAINABLE PATHWAYS

The future of nanomaterials in geoscience will be in the creation of sustainable, eco-friendly, and technologically sophisticated means of Earth system management. With increasing need for efficient use of resources and environmental protection, scientists are concerned with the integration of nanotechnology and geoscience models in solving geological and environmental problems. The one area that is highly promising includes the synthesis of nanoparticles using plant extracts, microorganisms, and biological organisms. It ensures that harmful chemicals are not used and the problem of environmental toxicity of the process is solved (Iravani, 2011). Another important developing domain is the combination of nanotechnology with remote sensing and geospatial technology. Sensors made from nanomaterials would greatly improve the performance of environmental monitoring devices, allowing for real-time monitoring of geohazards like landslides, earthquakes, groundwater pollution, and soil degradation. Moreover, novel hybrid nanomaterials with unique properties of adsorption, catalysis, magnetism, and sensing provide new possibilities for mineral exploration, pollution treatment, and groundwater purification (Khin et al., 2012).

The concept of implementing circular economy in the context of nanogeoscience is also anticipated to become another critical aspect for the future. The recycling and recovery of nanomaterials from industrial byproducts and waste streams will allow for minimizing resource consumption and sustainable industrial processes. Moreover, the creation of a policy framework associated with the use of nanotechnology for achieving the United Nations SDGs will be an important condition for the ethical implementation of these developments and ensuring safety for the environment (Roco, 2011). In summary, the integration of nanotechnology, geoscience, artificial intelligence, and data analytics will enable radical changes in the comprehension, observation, and management of resources on our planet.

Future research is likely to emphasize the integration of nanomaterials with geoscience models for holistic Earth system management. Priorities include:

- **Green synthesis** of nanoparticles using plant extracts and biological agents to reduce toxicity (Iravani, 2011).
- **Coupled nanotechnology and remote sensing** for high-resolution monitoring of geohazards.
- **Hybrid nanomaterials** combining adsorptive, catalytic, and sensing properties tailored for geoscientific challenges.
- **Circular economy approaches**, such as recycling nanomaterials from industrial waste streams for geoscientific applications.
- **Policy frameworks** linking nanotechnology with sustainable development goals (SDGs) to ensure ethical use and equitable benefits (Roco, 2011).

6. FUZZY LOGIC MODEL FOR NANOMATERIALS IN GEOSCIENCE

Fuzzy logic serves as a good platform to measure the sustainability performance of nanomaterials in the field of geoscience, considering various interacting environmental, technical, and economical factors in uncertain circumstances (Zadeh, 1965). Geoscience involves the use of nanomaterials in mineral exploration, water treatment, carbon capture and storage (CCS), enhanced oil recovery, and environment monitoring. The sustainable effect of such applications of nanomaterials in the field of geoscience can be measured using the fuzzy inference system, and a Sustainability Impact Index (SII) can be obtained from the measurement.

Let:

- X_1 = Resource Exploration Efficiency (REE)
- X_2 = Environmental Remediation Potential (ERP)
- X_3 = Carbon Capture and Storage Efficiency (CCSE)
- X_4 = Energy Resource Optimization (ERO)
- X_5 = Ecological Risk Reduction (ERR)

The output variable is:

Y = Sustainability Impact Index (SII)

The fuzzy function can be expressed as:

SII = f (X_1, X_2, X_3, X_4, X_5)

or through a weighted fuzzy aggregation model:

$Y = [\ \sum_{i=1}^{5} wi\ \ \mu i\ (Xi)\ /\ \sum_{i=1}^{5} wi]$

Where wi represents the relative importance of each criterion and μi (Xi) denotes the corresponding membership value (Zimmermann, 2010).

The linguistic variables for each input are categorized as Low (L), Medium (M), and High (H), while the output Sustainability Impact Index is classified as Very Low (VL), Low (L), Moderate (M), High (H), and Very High (VH). Triangular membership functions are commonly employed to represent these fuzzy sets due to their simplicity and computational efficiency (Ross, 2010).

Sample fuzzy rules include:

- **Rule 1:** IF REE is High AND ERP is High AND CCSE is High, THEN SII is Very High.
- **Rule 2:** IF REE is Medium AND ERP is High AND ERR is Medium, THEN SII is High.
- **Rule 3:** IF ERP is Low OR ERR is Low, THEN SII is Low.
- **Rule 4:** IF REE is High AND ERO is High AND ERR is High, THEN SII is Very High.

The fuzzy framework proposed in this paper can be used to assess the implications of nano-material based technologies on sustainability in the earth system by using various geoscientific indicators in an environment of uncertainty. Models like these can be used for evidence-based decision making in resource management, environmental remediation and climate change mitigation projects (Hochella et al., 2019; Karn et al., 2009). Earth systems often include elements of uncertainty, limited information and nonlinearity among environmental factors. Fuzzy logic is well suited for developing models and assessing the sustainability impact of nanomaterial based technology through integration of various data sets. Through inclusion of various factors such as efficiency of resource exploration, environmental remediation capacity, carbon sequestration, energy efficiency and ecological risk reduction, a sustainability impact index (SII) can be developed using fuzzy inference models (Ross, 2010).

7. FUTURE RESEARCH DIRECTIONS

The future direction of research will be the design of environmentally safe and biodegradable nanoparticles that would reduce the risk of any ecological damage and enhance the geoscience value of the application. The combination of the fields of artificial intelligence, machine learning, digital twin and fuzzy decision support system along with nanotechnology will offer new possibilities for the sustainable management of Earth system. In addition, LCA studies need to be conducted to estimate the long-term environmental impact of nanomaterials.

7. CONCLUSION

Nanomaterials have become the key instruments in geoscience by providing new, innovative, and sustainable ways to develop natural resources, rehabilitate the environment, capture the greenhouse gases, optimize energy processes, and control geohazards. Unique physicochemical characteristics of the nanomaterials contribute substantially to the improvement of the efficiency, accuracy, and sustainability of the application of Earth system technologies. On the other hand, the extensive use of nanotechnology also requires addressing the possible adverse effects related to the environmental impacts, potential toxic effects, economics, and regulations. The implementation of fuzzy logic to assess the nanomaterials provides a powerful decision-support framework aimed at resolving uncertainty-related issues in relation to complex geoscientific systems. Using several sustainability criteria simultaneously, the proposed fuzzy framework will enable a complete assessment of the performance and environmental impact of the nanomaterials. The further interdisciplinary studies, development of green nanotechnologies, and appropriate governance will play an important role in achieving such objectives. Overall, the combination of the nanomaterials and fuzzy decision-support models can provide a way to sustainable management of the Earth system.

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