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Polyethyleneimine-Functionalized Nanostructures for Enhanced CO_2 Capture: Technological Prospects, Policy Implications and Sustainability

Jasmine Wei

E-mail: jasminewei0327@gmail.com

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Abstract

Enhanced CO_2 capture via Polyethyleneimine-loaded (PEI) mesoporous silica nanoparticles and PEI-functionalized carbon nanotubes (CNTs) provides a promising pathway towards efficient carbon capture. The incorporation of PEI onto the silica surface leads to enhanced interactions with CO_2, resulting in significantly improved capture performance. These PEI-loaded mesoporous silica nanoparticles demonstrate exceptional carbon capture rates, indicating their potential for diverse sequestration applications in the future. However, given the dynamic nature of nanoparticle research, it is imperative for public policies to comprehensively address the entire life cycle of these materials, encompassing manufacturing, usage, and disposal, with a strong emphasis on promoting sustainable practices and minimising any adverse impacts. Effective collaboration among researchers, industry stakeholders, and the public is vital to establish a transparent decision-making process that ensures the responsible and sustainable utilisation of these nanoparticles. Integrating robust public policies assists the widespread adoption and implementation of PEI-loaded mesoporous silica nanoparticles, contributing to effective carbon capture and addressing the urgent challenges posed by climate change.

Keywords: Polyethyleneimine, mesoporous silica, carbon nanotubes, carbon capture, nanoparticles, toxicity, production, usage, disposal, sustainability, public policy.

1. Introduction

The increase in CO_2 emissions is one of the prevalent reasons for global warming. Many efforts have been applied to restabilize the CO_2 concentration within the atmosphere. Since the main emission of CO_2 is burning fossil fuels, carbon sequestration at power plants and industrial factories has proven to be an efficient method of removing CO_2 from the atmosphere [1]. Carbon sequestration functions by capturing the CO_2 from the source of CO_2 emission, then storing it in vegetation, called biological carbon sequestration, in rocks, called geological carbon sequestration, or treating it as a resource, called technological carbon sequestration.

Recent technological advancements in nanoscience demonstrated the ability of NPs to capture carbon dioxide. One of the most promising nanoparticles was PEI, with the CO_2 adsorption capacity for air capture to be at most 7.3wt%, one of the highest wt% by nanoparticles [2]. To maintain the chemical and mechanical stability for PEI, mesoporous silica was found to be the best impregnator given its chemical and mechanical stability. Another addition includes the PEI-functionalized CNTs. From the different materials, CNTs may be easier to create; plastics can be pyrolyzed at 800°C to produce CNTs. [3] This process aids in removing plastics from ocean pollution, with one of the garbage patches, the Great Pacific Garbage Patch, over three times the size of France. The boundless supply of plastics would permit CNTs to be produced without limits, and many of the CNTs can be used with PEI.

However, given the new use of technology, public policy considerations are important regarding the regulation of NPs. Challenges include the long-term environmental impact of nanoparticle release, appropriate regulations for production and usage, and economic feasibility. Addressing potential health and safety risks associated with nanoparticle exposure is also crucial. Consequently, many guidelines must be in place to ensure human and environmental safety, along with consistent efficiency to annually lower CO_2 emissions.

1.1 PEI effectiveness

PEI has been extensively researched since the 1990s. [4] PEI comes in either branched or linear structures, where branched PEI may contain primary, secondary, and tertiary amino groups and linear PEI solely contains primary and secondary amino groups. [5] Though both structures can capture CO_2, linear PEI works slightly more efficiently. [6] Silica was reported as a functional support for a PEI sorbent, where PEI could covalently bond with silica gels and retain silica properties. Thus, many mesoporous silicas can be used, including MCM-41, MCM-48, SBA-15, SBA-16, and KIT.

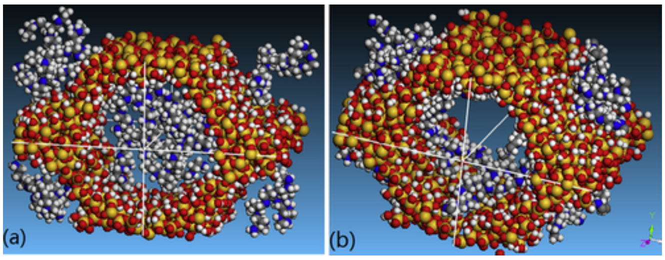

Figure 1: The Structure of a PEI-loaded MCM-41 nanoparticle before and after optimization. Figure from [6]

Studies found the CO_2 captures with all the aforementioned silica gels and the adsorption capacities from highest to lowest magnitudes are as follows:

KIT-6≈SBA-16>SBA-15>MCM-48>MCM-41 [7]

The ability of the PEI impregnated silica gels were correlated by the pores within the silicas. KIT-6 had the largest pores and demonstrated a CO_2 adsorption capacity of $135\,mg/g$ at 75°C. There was an increase in adsorption capacity, at a rate of $190\,mg/g$ at 75°C, when the high surface area silica was sandwiched between graphene sheets. [8] PEI can also be attached to carbon nanotubes by covalent bonding and adsorb CO_2, though lower temperatures were found to reap better results. The PEI-functionalized CNTs had a maximum adsorption capacity of $121.2\,mg/g$ in the range of 60-75°C.

The PEI silica and CNT both had uses depending on the temperature range required in whichever location required capturing carbon. With the adsorption capacities ranging from around $120 - 190\,mg/g$ in a rapid timeframe, the CO_2 can be captured, rapidly sequestered, and the PEI silica or CNT is ready to capture again.

1.2 Manufacturing Policy Regarding NPs

If PEI is to be utilised in the future, meeting the necessary requirements will require optimizations in nanoparticle manufacturing processes. Currently, NPs can be manufactured through either a top-down or bottom-up approach. The top-down process involves breaking down material into NP size for utilisation, while the bottom-up process employs chemical and physical forces at the nanoscale to create nanoscale structures.

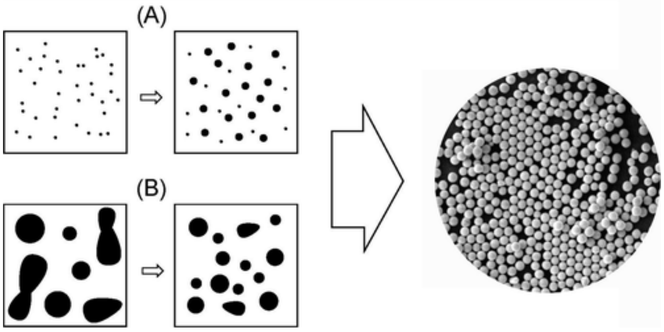

Figure 2: The top down and bottom up approach in synthesizing nanoparticles. Figure from [9]

Although the top-down process is faster, mass production of NPs has not been achieved. To effectively employ NPs in addressing global issues such as CO_2 pollution, automated or larger-scale manufacturing of NPs becomes imperative. However, it is crucial that no compromises are made on the quality of NPs by rushing the manufacturing process. Therefore, future policies should focus on ensuring product assurance, wherein NPs, such as PEI, maintain consistent chemical structures and functional groups.

Each NP should have a requirements sheet specifying the necessary criteria for classification as a specific type of NP. Regular monitoring and inspection of chemical engineering processes are necessary to ensure the accurate production of NPs. Any deviations or alterations in manufacturing, whether intentional or accidental, should only occur after thorough testing and unanimous agreement. Changes in chemical reactions could lead to unforeseen and potentially harmful consequences. Lastly, to promote transparency and informed decision-making, policies should mandate manufacturers and producers of nanoparticle-containing products to disclose the presence of NPs and provide information about potential risks. Implementing labelling requirements plays a critical role in enabling consumers to make informed choices and facilitating effective monitoring by regulatory agencies across various product categories.

1.3 Usage Policy Regarding NPs

Policies should address the potential environmental impacts stemming from nanoparticles, including their release into the air, water, or soil during manufacturing, usage, and disposal stages. The establishment of regulations and guidelines can help manage nanoparticle waste and prevent uncontrolled release, thereby minimising their adverse environmental effects. To safeguard the health and well-being of workers involved in industries that handle nanoparticles, there should be policies focused on implementing guidelines and standards aimed at minimising occupational exposure. This includes the provision of appropriate personal protective equipment and the requirement of safe handling and disposal practices.

Governments can play a pivotal role in supporting research and development endeavours aimed at comprehending the potential benefits and risks associated with nanoparticles. However, it must be a branch of government with the knowledge of mastered comprehension of NPs. For certain NPs to be of function, like PEI, there must be substantial research in the field in which it will be used to certify safety. Though this policy may stagnate growth in fields, it ensures human safety and fewer catastrophes. Given the global nature of nanoparticle production and usage, international cooperation is essential in establishing consistent standards and regulations. Policymakers should collaborate to harmonise guidelines, share best practices, and exchange information pertaining to the safe and sustainable use of nanoparticles. This cooperation fosters a collective effort in addressing challenges and promoting responsible practices across borders.

Public policy may encompass initiatives that aim to enhance public awareness and understanding of nanoparticles, including their benefits and potential risks. This can be achieved through educational campaigns, public consultations, and efforts to engage stakeholders from diverse backgrounds, such as consumers, industry representatives, and environmental groups. By promoting public awareness and education, policymakers can foster a more informed and engaged society regarding nanoparticles and their implications.

1.4 Disposal Regarding PEI Silica and CNTs

PEI has shown many side effects on humans. Using polycations to deliver PEI to cells, PEI has caused high levels of cytotoxicity. [10] The NP is widely used as a gene delivery nanosystem and induces apoptosis/necrosis. [11] Consequently, it is paramount that if used for carbon sequestration, PEI cannot be entered into a human body's systems. Currently, though PEI is used in drug delivery, entering our systems to combat cancers, it is done under heavy scrutiny and medical procedure. While it remains true PEI can be continuously used, PEI must be disposed of in laboratory fashion. All nanomaterial waste, including PEI, is labelled as hazardous waste, and PEI can be soaked up by adsorbents if it leaks or spills. However, to dispose of PEI, it must be dissolved by a combustible solvent and burned in a chemical incinerator. Thus, for factories to use PEI, there must be regulations regarding the use of PEI by a professional in the field and the proper equipment at the location to dispose of PEI.

Mesoporous silica are widely used materials, and instead of disposing of the material, it can be recycled. Patented by Jong-Sung Yu, mesoporous silicas can first undergo carbonisation, becoming carbonised mesoporous silicas, and added to silica waste to become recycled mesoporous silica. [12] The recycled version still has a lot of use and can be applied in many other different fields.

CNTs are also considered hazardous waste, and exposure to CNTs can cause inflammation, injury, fibrosis, and pulmonary tumours. [13] CNTs also have different structures and can come in lengthy shapes and, if it enters our environment, may cause serious harm to surrounding people.

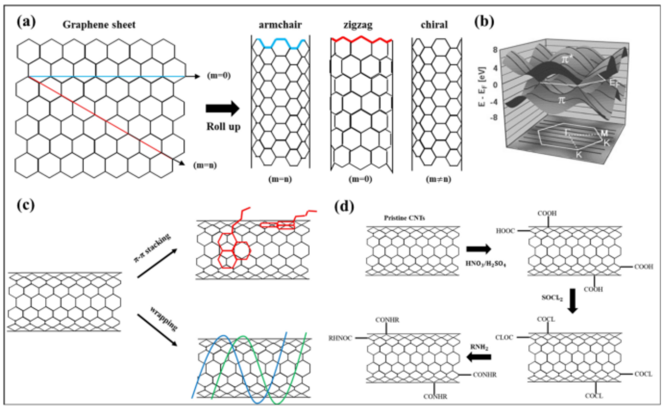

Figure 3: The multiple CNT structures each with their own unique structures. Figure from [14]

Additionally, given CNT tensile strength and durability, it may be a future building material as well. Consequently, CNTs may enter the same living environment as humans, and may need additional chemical advancements to be inhabitable by humans. But currently, to dispose of CNTs, a possible degradation method is to add a degradable sulfhydryl compound containing a triazine ring. The triazine ring adds stability and increases the functionalization of CNT as a film-like material, and the CNT can be recycled by solely degrading the triazine ring in acid treatments. [14]

1.5 Future Use of PEI Silica and CNTs against Climate Change

While the research points to PEI silica and PEI-functionalized CNTs being used for carbon sequestration, there are other possible functions for the materials. The carbon sequestration within many power plants and factories will limit the CO_2 emissions, but will not reduce the CO_2 already in the atmosphere. Current technologies cannot reduce the current CO_2, but in the future, these NP structures could be placed around the troposphere, the atmosphere CO_2 resides in, to reduce the ppm in the air. The PEI silica and PEI-functionalized CNTs could be placed on aircrafts, on drones that could patrol the sky, or on other possible inventions to capture CO_2 and sequester it.

PEI and CNTs both have their own unique properties and can be used for other functions. Besides being used for CO_2 adsorption and drug carriers on the nano level, PEI can be used for other synthetic polymers. [15] PEI can be used as a corrosion inhibitor. For many metal substrates, including different types of steel, copper, NaCl, PEI reduces pitting corrosion at a high performance. CNTs tensile strength allows for the reinforcement of steel alloy, and the possible creation of CNT alloys in the future if the toxicity is somehow removed. If mass-manufactured, CNTs can reshape the world and substitute for many construction materials, like roads, buildings, architecture, etc.

1.7 Conclusion

PEI functionalized nano-structures have experimentally demonstrated the ability to combat CO_2 pollution. To ensure the utilisation of PEI, public policy for manufacturing, usage, and disposal must be closely adhered to for safety and optimization. Policies may include the assurance of product and labelling, the safeguard, education, and regulation by experts in the field, and the proper laboratory methods of disposal. PEI and CNTs use range out of CO_2 pollution as well, with CNTs having multifarious construction utility and PEI's important drug delivery against cancers and corrosion inhibitors. The future of nanoscience and nanotechnology remains bright and an important field to combat international issues and pioneer human ingenuity under sustainable practices.

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