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Educational strategies for future engineers: understanding nano-adsorbents in carbon capture and storage technologies

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ABSTRACT

Climate change and increasing carbon dioxide (CO_2) emissions demand technological innovations that can support effective climate change mitigation. One of the rapidly growing solutions is the use of nano-adsorbents in carbon capture and storage (CCS) technology, which is able to improve CO_2 absorption efficiency through high surface area and adjustable porosity. However, although the effectiveness of this technology has been proven in various studies, its integration in engineering education is still limited, so aspiring engineers lack sufficient understanding and skills in implementing this solution in the industrial world. This research aims to develop a systematic educational strategy to integrate nano-adsorbent learning in the engineering curriculum, by emphasizing an experiential approach and industry collaboration. The study used a blended method, which combined qualitative insights from interviews and focus groups with quantitative data from surveys of students and engineering faculty. The results showed that 68% of students did not get adequate exposure to nano-adsorbent technology, while 84% of respondents supported the addition of related materials in the engineering curriculum. In addition, only 35% of students have direct experience with this technology through labs or industrial internships, indicating the need for reform in the engineering learning system. As a contribution to the academic literature, this research provides an innovative educational model that combines nano-technology with sustainability-based engineering learning strategies. By proposing curriculum reforms, improved laboratory access, as well as partnerships with the CCS industry, the research not only provides concrete solutions for academia but also contributes to strengthening the skills of future engineers in low-carbon technologies. The implementation of this model is expected to increase the readiness of engineering graduates to support the transition to a more environmentally friendly industry and accelerate climate change mitigation through more effective CCS technology.

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Introduction

Accelerating climate change has raised urgent demands on the development of sustainable technologies that can reduce greenhouse gas emissions. One of the main proposed solutions is Carbon Capture and Storage (CCS), which aims to reduce carbon dioxide (CO_2) concentrations in the atmosphere through advanced technology. In recent years, nano-adsorbents have become a major concern in the field of CCS due to their ability to capture CO_2 with high efficiency, thanks to their large surface area and adjustable porosity (Mazari et al., 2022). However, although this technology continues to develop, its integration in engineering education is still very limited, thus hindering the readiness of future engineers to apply these technology solutions in the industrial world (Alrbaihat, 2024).

One of the fundamental problems in engineering education today is the gap between technological developments and learning in academic institutions. Most engineering curricula still rely on conventional teaching methods, which often only cover general principles of sustainability and environmental management without introducing new, more specific technologies, such as nano-adsorbents (Nworie, 2024). This leads to a skills gap between engineering graduates and industry demands, where future engineers do not have enough competencies to contribute to CCS technological innovation (Firdaus et al., 2021).

Furthermore, the lack of practice-based training is also a major obstacle. Many educational institutions still prioritize theoretical approaches without providing hands-on experience in the use of nano-adsorbents for CCS. As a result, engineering graduates are unfamiliar with the real challenges in the implementation of nano-material technologies, which ultimately hinders their contribution to the transition to low-carbon industries (Nazir, 2018). Increased global commitment to climate change mitigation as reflected in the Paris Agreement and international sustainability policies. With the industry increasingly shifting to low-carbon technologies, the need for an engineering workforce that understands cutting-edge solutions such as nano-adsorbents in CCS is urgent (Reza et al., 2023). Without an educational framework that supports the mastery of this technology, the engineering workforce will struggle to meet the demands of the industry and face the challenges of future sustainability technologies.

Although many studies have addressed the effectiveness of nano-adsorbents in improving the efficiency of CCS, studies on how these technologies are taught to future engineers are still limited (Haghi & Thomas, 2015). In addition, although the literature on sustainability education in engineering already exists, the existing approach is still general and not yet specific to nano-adsorbent technology. For instance, research by (Kumar et al., 2024) highlighted the importance of nano-materials in enhancing CO_2 capture efficiency, yet their study did not extend to how this knowledge could be effectively conveyed to future engineers. Similarly, (Adegoke et al., 2023) explored the optimization of nano-adsorbents for industrial use, but did not address how these innovations could be integrated into educational programs. Thus, there is a need for a novel approach that links technological advancements with educational strategies.

Moreover, prior research in engineering education has primarily concentrated on teaching broad sustainability principles or general technological innovations without focusing on specific, emerging technologies like nano-adsorbents. For instance, (Nassar & Hussain, 2023) emphasize the need to include more comprehensive sustainability modules in engineering programs, but fail to address how specialized technologies can be incorporated into these modules. Similarly, (Palit & Hussain, 2020) examined the role of engineering education in promoting sustainability but did not explore the specific role that nano-materials could play in this context.

This study contributes to the literature by addressing the identified gap and proposing educational strategies that incorporate nano-adsorbents into the engineering curriculum. The novelty of this research lies in its interdisciplinary approach, which combines insights from both engineering education and nanotechnology to design a framework for future engineers (Arshi et al., 2024). By focusing on nano-adsorbents and their application in CCS, this study provides a targeted educational model that aligns with the current technological trends and the urgent need for sustainable solutions in engineering practice.

The primary objective of this research is to develop and propose effective educational strategies that can be adopted by engineering institutions to enhance the understanding of nano-adsorbents among future engineers. The proposed strategies aim to provide students with both theoretical knowledge and practical skills, enabling them to apply these technologies in real-world environmental engineering contexts (Verma et al., 2023). By doing so, the study seeks to bridge the gap between current educational practices and the demands of the evolving technological landscape in CCS.

In contrast to previous research, this study emphasizes an interdisciplinary approach that combines engineering education in sustainability, nanotechnology as a CCS solution through nano-adsorbents, and practice-based pedagogical strategies that prioritize hands-on experience in laboratories and industry. This approach not only provides new insights in engineering education, but also results in a curriculum model that can be applied to equip aspiring engineers with practical skills in sustainability technology (Prabhu et al., 2023). This approach not only enhances students' technical proficiency but also fosters critical thinking and problem-solving skills, which are essential in addressing the multifaceted challenges of climate change (Sarkodie et al., 2024).

The unpreparedness of engineering workers in implementing CCS technology can hamper climate change mitigation efforts, especially if engineering education does not immediately adapt to technological developments. This risks creating difficulties in meeting the needs of green industries, lack of innovation in climate change mitigation, and a gap between academic research and its application in industry. Therefore, this research has become very relevant for educational institutions and industry in accelerating the transition to low-carbon technology. Through engineering education reform, the research bridges the gap between theory and practice, ensuring that future engineers are able to innovate in CCS technology for global sustainability.

The expected outcome of this research is the development of a comprehensive educational framework that integrates nano-adsorbents into engineering education. This framework will not only benefit students by enhancing their knowledge of CCS technologies but also contribute to the broader goal of equipping the engineering workforce with the necessary tools to drive sustainable innovation (Koduru et al., 2023). The framework will be designed to be adaptable to different educational contexts, ensuring its applicability across a range of engineering disciplines and institutions.

This research aims to integrate nano-adsorbent learning in the engineering curriculum by identifying the main challenges, designing experience-based strategies, and developing effective curriculum implementation models. The results are expected to enrich academic literature and provide real solutions for engineering education in facing the challenge of climate change.

Method

This study adopts a mixed-method research approach that combines qualitative and quantitative methods to explore educational strategies in integrating nano-adsorbents into the engineering curriculum, especially in the context of carbon capture and storage (CCS). This approach was chosen to gain a comprehensive understanding of the challenges and opportunities of the integration of these technologies in engineering education, by combining insights from empirical data and subjective perspectives from experts and students (Creswell & Creswell, 2017). By combining qualitative insights from expert interviews and focus groups with quantitative data from surveys and curriculum analysis, the study aims to provide a holistic understanding of how nano-adsorbent technologies can be effectively incorporated into engineering education (Suharsaputra, 2012).

The study used an exploratory-descriptive research design to identify gaps in nano-adsorbent-related engineering curricula through interviews with academics, CCS professionals, and students. In addition, this study measures the level of awareness and perception of students and educators towards the integration of nano-adsorbents in the curriculum through surveys, and analyzes the relationship between academic and industry perceptions of CCS and their readiness to adopt nano-material-based innovations. This approach ensures that research is not only conceptual, but also applicable in the practice of engineering education.

The data in this study were collected through three main methods: semi-structured interviews, focus group discussions (FGDs), and quantitative surveys. Interviews were conducted with 15 environmental engineering educators, 10 nano-materials scientists, and 10 CCS professionals to explore the challenges of nano-adsorbent integration in engineering education. The group discussion involved 30 engineering students from various universities to delve into their experiences with the curriculum and exposure to nano-adsorbent technology. Meanwhile, a quantitative survey with 150 engineering students and faculty members from various universities was conducted to measure the level of awareness, understanding, and support for the integration of nanotechnology in the curriculum. Data was collected through online and offline interviews.

This study uses qualitative and quantitative analysis to process the data collected. Data from interviews and group discussions were analyzed using thematic analysis, through an open-ended coding process, theme identification, and drawing conclusions based on patterns in participants' responses. Meanwhile, the survey data was analyzed quantitatively using descriptive statistics such as mean, median, and standard deviations to describe the perception of participants. Logistic regression analysis was used to explore the relationship between awareness of nano-adsorbents and participants' willingness to adopt curriculum innovations, as well as reliability tests with Cronbach's Alpha (≥ 0.7) ensuring the internal consistency of the survey instruments.

To ensure data quality, this study applies various validation techniques, including data triangulation by comparing insights from interviews with survey results and using education policy documents as secondary sources. The validity of the instrument was tested on the initial 20 respondents to identify potential biases, while the inter-coder test was conducted by two independent researchers to ensure objectivity in the thematic analysis. A mixed-methods approach is used because qualitative data provides deep insights into academic experiences and perspectives, while quantitative data allows for large-scale measurements of perceptions of the academic and industrial communities. The combination of these two methods ensures more comprehensive and applicable results in the development of evidence-based education strategies. The selection of the sample was carried out by purposive sampling for interviews and FGDs, targeting participants with expertise in environmental engineering and nano-materials, as well as stratified random sampling for surveys to ensure a proportional representation of various academic and professional backgrounds.

Results and Discussions

This study aimed to explore effective educational strategies for integrating nano-adsorbents into engineering curricula, particularly in the context of carbon capture and storage (CCS) technologies. The mixed-methods approach, combining qualitative interviews and focus groups with quantitative survey data, provided a comprehensive understanding of the current state of engineering education and the potential for incorporating emerging technologies like nano-adsorbents.

Table 1. Survey Distribution Data

Metric	Count
Total Survey Distributed	150.0
Response Rate (%)	75.0
Total Responses	112.5

The survey was distributed to 150 engineering students and faculty members from various universities, with a 75% response rate. The quantitative data revealed a significant gap in the current curriculum regarding the inclusion of advanced technologies like nano-adsorbents. Approximately 68% of students reported that their courses primarily focused on traditional environmental engineering methods, with minimal exposure to cutting-edge technologies such as nano-materials and CCS systems. Furthermore, 84% of respondents expressed the need for more specialized content related to emerging sustainability technologies in their curriculum.

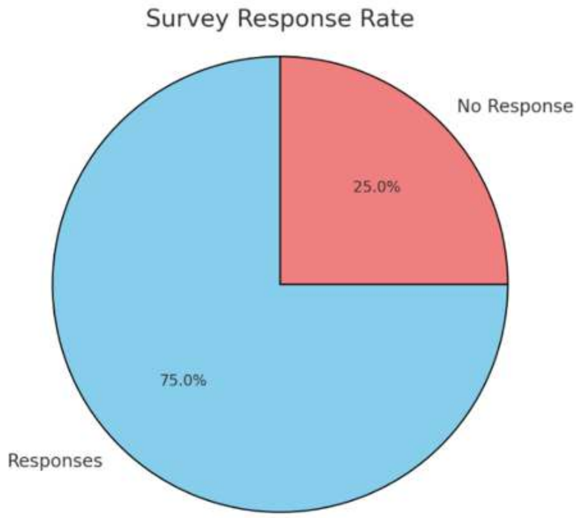

Figure 1. Response Rate

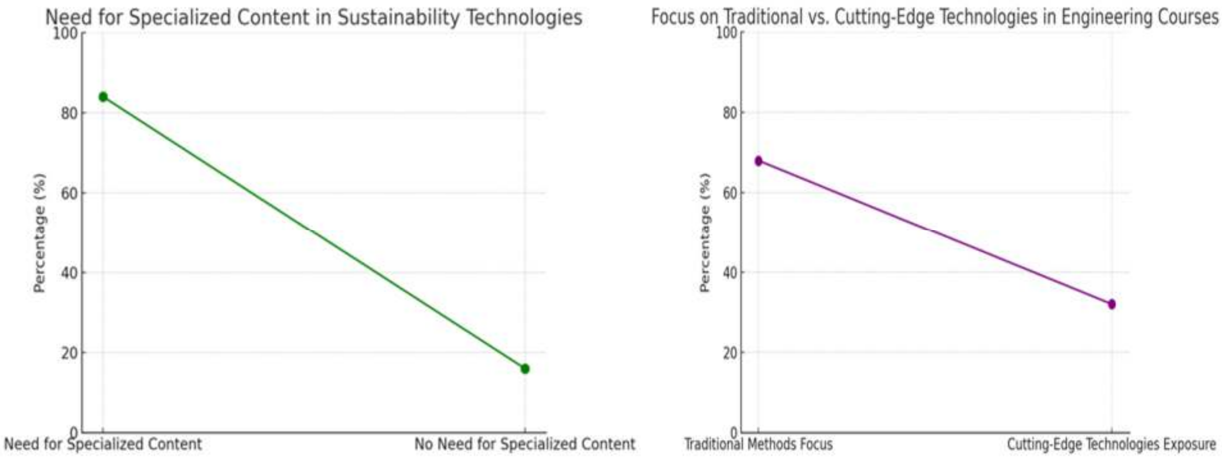

Figure 2

A Likert scale was used to assess attitudes toward the inclusion of nano-adsorbents in engineering education. Results showed that 72% of students and faculty agreed that understanding nano-materials is crucial for future engineers, particularly in the context of addressing climate change through CCS technologies. However, only 35% of respondents reported having any hands-on experience with these technologies in their coursework or internships.

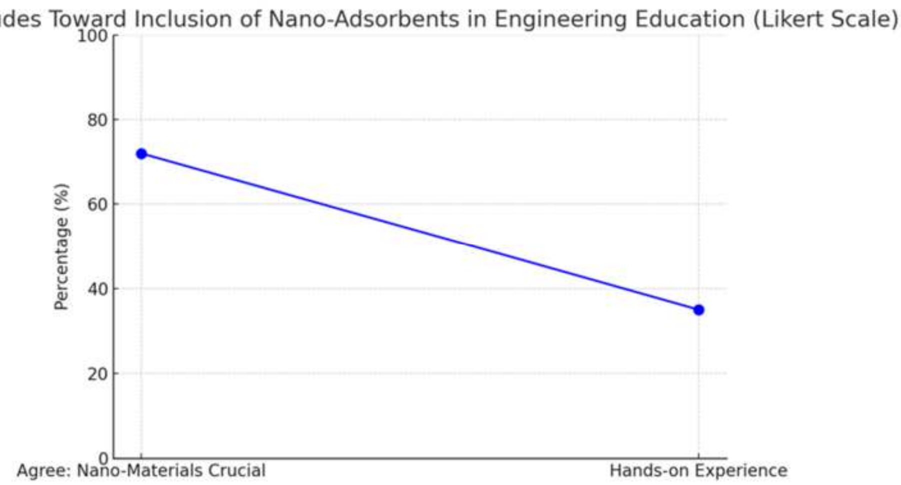

Figure 3

Qualitative Findings

The qualitative interviews and focus groups provided deeper insights into the challenges and opportunities of incorporating nano-adsorbents into engineering programs. Educators highlighted the difficulty in updating curricula to include new technologies due to rigid academic structures and limited resources. As one faculty member noted, "There is a clear need for more updated content, but integrating it requires institutional support, which is often lacking." Another challenge identified was the lack of practical learning opportunities for students to experiment with nano-materials, as many universities lack the necessary lab equipment and partnerships with industry to facilitate this.

However, both educators and students expressed enthusiasm for the potential of nano-adsorbents as a key technology in mitigating climate change. Several interviewees suggested that collaborations with industry could help bridge the gap between academia and real-world applications of nano-adsorbents. One interviewee remarked, "Partnerships with companies working on CCS technologies could provide students with valuable hands-on experience and exposure to how these materials are being used in the field."

The Need for Curriculum Reform

The results of this study indicate a clear gap in engineering education, particularly in the inclusion of advanced technologies like nano-adsorbents for CCS. As noted in the literature, nano-adsorbents offer significant potential in enhancing the efficiency of carbon capture technologies (Aravind & Kamaraj, 2024). However, despite their importance, these technologies are not adequately covered in current engineering programs, leaving students unprepared to work with these materials in their future careers. This finding aligns with previous studies that highlight the slow pace of curriculum reform in engineering education, particularly in response to emerging environmental challenges (Palit, 2018).

The survey data suggests that there is a strong demand among students and faculty for more specialized content related to nano-materials and CCS technologies. This supports the argument made by (Hussain, 2020), who emphasized the need for educational programs to evolve in response to technological advancements. By incorporating nano-adsorbents into the curriculum, engineering programs can better prepare students to contribute to the development and implementation of CCS technologies, which are critical for achieving global climate goals.

The rapid advancements in technology and the growing environmental challenges, such as climate change, have created a critical need to reform engineering curricula. Traditional engineering education has historically focused on foundational principles and well-established technologies. While these are essential, the pace at which new technologies like nano-adsorbents and carbon capture and storage (CCS) systems are developing requires that curricula evolve to keep pace with these innovations. Current engineering programs are often criticized for being slow to adapt to emerging technologies, which can leave students unprepared to tackle the complex, interdisciplinary challenges of modern environmental engineering (Sen et al., 2023).

One of the main reasons for this reform is the increasing importance of nano-adsorbents in carbon capture technologies. Nano-adsorbents, due to their high surface area and selective adsorption properties, offer significant potential in reducing CO_2 emissions, making them a crucial technology in the fight against climate change (Penchah & Maleki, 2024; Shukla et al., 2020). However, despite the importance of this technology, most engineering students report minimal exposure to it during their studies. A survey revealed that 68% of students felt their courses primarily focused on traditional environmental engineering methods, with little emphasis on cutting-edge technologies like nano-materials and CCS. This gap between emerging technologies and educational content highlights the need for curriculum reform that incorporates such advanced topics into the learning experience.

Incorporating cutting-edge technologies such as nano-adsorbents into the curriculum not only provides students with a deeper understanding of these innovations but also equips them with practical skills that are essential for real-world applications. As industries shift towards more sustainable practices and seek to reduce their carbon footprint, engineers with specialized knowledge in nano-adsorbents and CCS will be in high demand (Tawiah et al., 2024. Without adequate training in these areas, students may struggle to apply theoretical knowledge to practical environmental problems, limiting their ability to contribute effectively to sustainable engineering solutions. Therefore, curriculum reform must focus on bridging the gap between theoretical knowledge and practical, hands-on experience with advanced technologies.

Another important factor driving the need for curriculum reform is the global push for sustainability and climate action. International agreements, such as the Paris Agreement, have set ambitious targets for reducing carbon emissions and limiting global temperature rise to below 2°C. Meeting these goals requires a workforce that is not only technically proficient but also well-versed in the latest sustainable technologies. Educational institutions have a critical role to play in developing this workforce by updating their curricula to include emerging technologies that can contribute to climate mitigation. Integrating nano-adsorbents into the curriculum aligns with these global sustainability goals and ensures that future engineers are prepared to meet the demands of a rapidly changing world.

Hands-on learning is also a crucial aspect of the reform. Traditional engineering education tends to focus heavily on theoretical knowledge, often at the expense of practical, hands-on learning opportunities. However, research has shown that experiential learning, where students apply theoretical concepts in real-world settings, is vital for developing the skills needed to innovate and solve complex problems (Bhattacharjee et al., 2024). For example, giving students the opportunity to work with nano-adsorbents in laboratory settings or through industry internships could significantly enhance their understanding of how these technologies function in practical applications. By fostering a more hands-on approach, curriculum reform can help future engineers gain the experience necessary to contribute to technological advancements in environmental sustainability.

Finally, curriculum reform should be seen as an ongoing process rather than a one-time adjustment. As technology continues to evolve, so too must the content and structure of engineering education. Educational institutions must establish mechanisms for regularly updating their curricula to reflect the latest technological advancements and industry needs. This may involve close collaboration with industry partners, who can provide insights into emerging technologies and ensure that the curriculum remains relevant. By continuously adapting to new developments, engineering programs can ensure that their graduates are equipped with the knowledge and skills necessary to thrive in an ever-evolving technological landscape (Prasad & Gupta, 2024).

In conclusion, the need for curriculum reform in engineering education is driven by several factors, including the rapid advancement of technologies like nano-adsorbents, the global push for sustainability, and the importance of hands-on learning. By incorporating emerging technologies into the curriculum, providing practical learning experiences, and maintaining a flexible, adaptive approach to education, institutions can prepare future engineers to tackle the environmental challenges of the 21st century. This reform is essential not only for equipping students with the skills they need but also for ensuring that engineering education remains relevant and aligned with the goals of sustainability and climate action.

Examples of nano-adsorbents used in carbon capture and other environmental applications include the following: (1) Carbon Nanotubes (CNTs): Carbon nanotubes are cylindrical structures composed of carbon atoms. Due to their high surface area, excellent mechanical properties, and chemical stability, CNTs are widely used as nano-adsorbents for capturing gases like CO_2. Their tunable surface properties allow for the modification of adsorption capabilities, making them highly effective in carbon capture processes (Shukla et al., 2020); (2) Metal-Organic Frameworks (MOFs): MOFs are porous materials composed of metal ions coordinated to organic ligands. Their high porosity and large surface area make them highly efficient for gas adsorption, particularly for capturing CO_2. MOFs have shown promise for selective gas adsorption and separation processes, which are critical for carbon capture and storage technologies (Tawiah et al., 2024); (3) Zeolites: Zeolites are crystalline aluminosilicates with a porous structure. They have been used for many years as adsorbents in gas separation due to their ability to selectively capture certain molecules based on size and charge. Zeolites are also used for CO_2 capture because of their tunable pore sizes and surface properties; (4) Graphene Oxide (GO): Graphene oxide is a modified form of graphene with oxygen-containing functional groups. Its large surface area and functional groups make it highly suitable for adsorption applications. GO is particularly effective in adsorbing heavy metals and organic pollutants in water treatment, as well as capturing CO_2 in air filtration and CCS systems; (5) Activated Carbon: Although not strictly a nano-material, activated carbon is widely used as an adsorbent in various environmental applications, including CO_2 capture. Its high surface area and pore structure allow for the efficient adsorption of gases and pollutants. Nano-sized activated carbon derivatives are also being developed for improved adsorption efficiency; (6) Silica Nanoparticles: Silica-based nano-adsorbents have been used for environmental cleanup and gas adsorption. Mesoporous silica nanoparticles, in particular, have a highly tunable pore structure and surface area, making them effective in the adsorption of pollutants and gases like CO_2.

These nano-adsorbents are continually being researched and developed to improve their efficiency, selectivity, and sustainability in carbon capture and other environmental applications.

Hands-On Learning and Industry Collaboration

One of the key challenges identified in this study is the lack of hands-on learning opportunities for students to engage with nano-adsorbents. While theoretical knowledge is important, practical experience is essential for developing the skills needed to apply these technologies in real-world contexts. Previous studies have emphasized the importance of experiential learning in engineering education, particularly in preparing students for the complexities of environmental engineering (Altalhi & Mazumder, 2023). The results of this study confirm that students and faculty alike recognize the value of hands-on learning but face barriers to implementing it due to a lack of resources and institutional support.

Collaborations with industry were identified as a potential solution to this challenge. As noted by several interviewees, partnerships with companies involved in CCS technologies could provide students with access to the equipment, expertise, and practical learning experiences that are currently lacking in many academic institutions. This finding echoes the recommendations made by (Tawiah et al., 2024) who argued that industry-academia collaborations are essential for bridging the gap between classroom learning and professional practice. By fostering these partnerships, engineering programs can offer students the opportunity to work with nano-materials in real-world settings, enhancing their understanding of the technology and its applications.

Hands-on learning is a critical component of modern engineering education, particularly when it comes to preparing students to engage with complex, real-world challenges. In the context of emerging technologies like nano-adsorbents and carbon capture and storage (CCS) systems, hands-on learning ensures that students can move beyond theoretical knowledge and develop the practical skills needed to apply these technologies effectively. Unlike traditional lecture-based learning, hands-on experiences provide students with the opportunity to directly interact with materials and technologies, deepening their understanding through experimentation and application (Nguyen et al., 2024). For engineering students, the ability to work with advanced materials like nano-adsorbents in laboratory settings allows them to see how these technologies perform under various conditions, preparing them for professional roles that demand technical expertise.

The integration of hands-on learning into engineering education becomes even more vital when considering the rapid advancements in technologies like nano-materials. Nano-adsorbents, due to their unique properties such as high surface area and selective adsorption capabilities, are highly promising in applications like CO_2 capture. However, their effectiveness depends on how well they are understood and applied in different scenarios (Mazari et al., 2022). By providing students with laboratory-based opportunities to test, manipulate, and optimize nano-adsorbents, educational programs ensure that future engineers are equipped with the knowledge necessary to drive innovations in carbon capture and other environmental applications. Hands-on learning not only enhances technical proficiency but also encourages critical thinking and problem-solving, which are essential skills for addressing environmental challenges.

Moreover, hands-on learning fosters creativity and innovation among students. When students are given the chance to experiment with materials and technologies in real-time, they are more likely to discover new ways of improving processes or creating novel applications. For example, working with nano-adsorbents in a laboratory setting could lead to insights about how surface modifications or chemical treatments could enhance the material's CO_2 adsorption capacity. These experimental opportunities enable students to think beyond the textbook and actively engage in the process of innovation, an essential mindset for engineers in the 21st century (Alrbaihat, 2024). By allowing students to "learn by doing," hands-on learning prepares them to become innovators who can contribute to the advancement of sustainable technologies.

However, providing meaningful hands-on learning experiences in advanced technologies like nano-adsorbents requires significant resources, such as specialized laboratory equipment and expert supervision. Many academic institutions may not have the financial or technical capacity to support these kinds of learning opportunities on their own. This is where industry collaboration becomes essential. Industry partnerships can bridge the gap between academic learning and real-world applications by providing students with access to cutting-edge technologies, equipment, and expertise that may not be available within the university (Nworie, 2024). For example, companies working on CCS technologies or the development of nano-materials can partner with universities to offer students internships, co-op programs, or project-based learning experiences that involve working with nano-adsorbents in practical settings.

Industry collaboration also enhances the relevance of the curriculum by aligning educational content with the needs of the workforce. Through partnerships with industry, academic institutions can ensure that their programs are preparing students with the specific skills and knowledge that employers are looking for. In the case of nano-adsorbents and CCS technologies, collaboration with companies at the forefront of these fields can help universities stay updated on the latest advancements and trends, ensuring that students are learning the most current and applicable content. Additionally, industry professionals can provide valuable insights and mentorship to students, helping them navigate the transition from academia to the workforce (Firdaus et al., 2021). These interactions give students a clearer understanding of the expectations and challenges they will face as engineers, making them better prepared for their careers.

Furthermore, industry collaborations often lead to research and development opportunities that benefit both the university and the industry partner. Companies looking to innovate in areas like carbon capture can benefit from the research capabilities of academic institutions, while universities gain access to industry-specific challenges and real-world data. These partnerships create a symbiotic relationship where both parties contribute to advancing technology and education simultaneously. For example, a company developing nano-adsorbents for CCS might partner with a university to conduct joint research on optimizing the material's performance, with students and faculty working alongside industry professionals to achieve shared goals. This not only enhances the educational experience for students but also accelerates technological advancements in the field (Nazir, 2018).

In conclusion, hands-on learning and industry collaboration are essential components of modern engineering education, particularly in the context of emerging technologies like nano-adsorbents and CCS systems. Hands-on learning equips students with the practical skills and critical thinking abilities needed to apply advanced materials in real-world settings, while industry collaboration provides the resources, expertise, and relevance necessary to ensure that educational programs remain aligned with technological advancements. Together, these approaches prepare students to become innovative engineers who can contribute to the development of sustainable technologies, addressing some of the most pressing environmental challenges of our time. By fostering both practical experience and industry engagement, universities can create a generation of engineers who are well-equipped to lead the way in fields like carbon capture and environmental sustainability.

Industry collaboration offers numerous benefits for both academic institutions and students, as well as for the companies involved. Here are some key benefits:

Access to Cutting-Edge Technologies

Industry collaborations often provide universities and students with access to the latest technologies and equipment, which may not be available within academic institutions due to budget constraints. Companies at the forefront of innovation in fields like nano-adsorbents or carbon capture technologies can offer students hands-on experience with state-of-the-art tools and methods, keeping their education aligned with real-world practices (Sen et al., 2023).

Enhanced Curriculum Relevance

Collaboration with industry ensures that the content of academic programs remains relevant to the current needs of the workforce. Through these partnerships, universities can tailor their curricula to reflect the latest trends, challenges, and innovations in the field. Industry experts can also provide insights into what skills are most in-demand, helping to ensure that graduates are job-ready (Palit, 2018).

Practical Learning Opportunities

Through internships, co-op programs, and project-based learning, students gain valuable practical experience that complements their theoretical knowledge. Industry collaborations allow students to work on real-world projects, providing them with an understanding of how the skills they learn in the classroom apply to professional engineering challenges (Koduru et al., 2023). This hands-on experience is essential in developing problem-solving skills and fostering innovation.

Job Placement and Career Advancement

Industry partnerships often serve as a bridge between education and employment. Companies collaborating with universities have early access to a pool of skilled graduates, which can lead to internships, full-time employment opportunities, and a smooth transition from academic life to the professional world. For students, this means greater exposure to potential employers and a higher likelihood of securing jobs in their field (Sarkodie et al., 2024).

Mutual Research and Development (R&D) Opportunities

Academic institutions often have strong research capabilities, and partnering with industry can lead to mutual R&D benefits. Companies can leverage university research expertise to explore innovative solutions, while universities can gain access to real-world data and industry-specific challenges. This collaboration accelerates technological advancements and ensures that academic research has practical, applicable outcomes (Firdaus et al., 2021).

Mentorship and Professional Networks

Industry professionals often serve as mentors to students during internships or collaborative projects, offering valuable career advice and guidance. This mentorship helps students gain insights into the engineering profession, industry expectations, and leadership development. Moreover, collaborations help students build professional networks that can be instrumental in their career growth (Nazir, 2018).

Overall, industry collaboration enriches the educational experience, strengthens the alignment between academic institutions and industry needs, and fosters innovation through shared resources and expertise.

The Role of Educational Strategies in Addressing Climate Change

Finally, the results of this study underscore the importance of developing educational strategies that align with global environmental goals, particularly in the context of climate change. Nano-adsorbents have the potential to play a critical role in reducing CO_2 emissions through more efficient carbon capture (Reza et al., 2023). However, for these technologies to be implemented on a large scale, there must be a workforce that is knowledgeable about their development and application. As this study demonstrates, engineering education must evolve to include these emerging technologies to ensure that future engineers are equipped to address the urgent environmental challenges facing the world today.

The proposed educational strategies—such as incorporating nano-adsorbents into the curriculum, fostering industry partnerships, and promoting hands-on learning—offer a practical roadmap for addressing the current gaps in engineering education. By implementing these strategies, educational institutions can not only enhance the technical skills of their students but also contribute to broader efforts to mitigate climate change through technological innovation.

Educational strategies play a crucial role in addressing climate change by equipping future engineers, scientists, and policymakers with the knowledge, skills, and attitudes necessary to tackle the complex environmental challenges the world faces today. As climate change increasingly threatens ecosystems, economies, and communities worldwide, education must evolve to focus on sustainability and environmental stewardship. Developing effective educational strategies that integrate climate science, sustainability principles, and emerging technologies like carbon capture and nano-adsorbents is essential for creating a workforce that can implement and innovate solutions to mitigate climate change.

One key aspect of these educational strategies is the inclusion of up-to-date content on climate science and emerging technologies. As the scientific understanding of climate change deepens and new technologies emerge, educational programs must adapt to provide students with the most relevant and current knowledge. For example, topics like carbon capture and storage (CCS) and the use of nano-adsorbents in reducing CO_2 emissions are critical to combating climate change but are often underrepresented in traditional engineering curricula (Haghi & Thomas, 2015). By integrating such content into courses, students are better prepared to work with advanced technologies that can help achieve global climate targets, such as those set by the Paris Agreement.

Additionally, educational strategies must emphasize interdisciplinary learning, as climate change is not an isolated issue but one that intersects with various fields, including engineering, economics, law, and social sciences. The complexity of climate change solutions requires professionals who can navigate multiple disciplines and understand how technical, economic, and social factors interact. For instance, engineers working on climate mitigation technologies must also understand the economic feasibility and policy frameworks that govern the adoption of these technologies. Educational strategies that encourage collaboration across disciplines enable students to develop holistic solutions that consider the multifaceted nature of climate change (Kumar et al., 2024).

Hands-on learning and experiential education are also critical components of educational strategies aimed at addressing climate change. Students need practical experience working with the technologies and methods they will use in the workforce. For instance, providing students with the opportunity to work with nano-adsorbents in laboratory settings or participate in field projects related to renewable energy can significantly enhance their understanding of how these technologies work in practice (Palit & Hussain, 2020). Such experiences also encourage students to develop problem-solving skills, think creatively, and innovate in ways that are essential for tackling the evolving challenges of climate change.

Another important educational strategy is fostering a sense of responsibility and agency in students regarding climate action. Addressing climate change requires a shift in mindset toward sustainable practices and long-term thinking. Educational programs should emphasize the role that individuals and industries play in contributing to climate change and the importance of ethical decision-making in engineering and technology. When students understand their potential impact as future professionals, they are more likely to pursue careers that align with sustainable development goals and advocate for policies and practices that mitigate climate change (Adegoke et al., 2023).

Lastly, collaboration with industry and policy leaders is crucial in developing educational strategies that are both practical and forward-looking. Industry partnerships can provide valuable insights into the skills and knowledge that are in demand in the workforce, ensuring that educational programs remain relevant to the needs of employers. For instance, companies working in renewable energy, sustainable construction, or CCS technologies can collaborate with universities to offer internships, co-op programs, and project-based learning opportunities that give students real-world experience. Similarly, collaboration with policymakers helps ensure that students are prepared to work within the regulatory frameworks that govern climate mitigation efforts (Arshi et al., 2024).

In conclusion, the role of educational strategies in addressing climate change is multi-dimensional and involves not only providing students with the technical knowledge they need to work with emerging technologies but also fostering an interdisciplinary, hands-on, and ethical approach to sustainability. As the world faces increasingly severe climate challenges, educational institutions have a critical responsibility to equip the next generation of engineers, scientists, and leaders with the tools they need to mitigate and adapt to these challenges. By adopting forward-looking educational strategies, institutions can help shape a workforce that can drive innovation, implementing effective solutions, and advocating for sustainable policies that will benefit both people and the planet.

Nano-adsorbents are already highly effective in various applications, including carbon capture, water purification, and air filtration, but several strategies can be employed to further improve their performance. Here are some key ways nano-adsorbents can be enhanced:

Surface Functionalization
Surface functionalization involves modifying the surface chemistry of nano-adsorbents to increase their selectivity and adsorption capacity for specific target molecules. For example, introducing functional groups (e.g., amine groups) onto the surface of nano-adsorbents can enhance their ability to capture CO_2 or other gases by increasing the number of adsorption sites (Nworie, 2024). Surface functionalization can also be tailored for specific pollutants or gases, making the adsorbents more effective applications like CO_2 capture, heavy metal adsorption, or volatile organic compound (VOC) removal.

Increasing Surface Area and Pore Size
The efficiency of nano-adsorbents largely depends on their surface area and pore structure. By engineering materials with higher surface areas and optimizing pore sizes, nano-adsorbents can capture more molecules per unit mass. Mesoporous materials, for example, can be designed with tunable pore sizes to facilitate the diffusion and adsorption of larger gas molecules, making them more efficient for applications like CO_2 capture and storage (Mazari et al., 2022). Improving the pore structure to allow faster diffusion rates also increases adsorption efficiency.

Multi-Functional Adsorbents
Combining different functionalities in a single nano-adsorbent can improve its performance across multiple environmental challenges. For instance, a single nano-adsorbent material might be designed to simultaneously capture CO_2 and remove harmful pollutants such as sulfur dioxide (SO_2) or nitrogen oxides (NO_x) from industrial emissions. This multi-functional approach can significantly reduce the complexity and cost of environmental management systems by tackling multiple pollutants with one material (Nazir, 2018).

Improving Stability and Reusability
The long-term stability and reusability of nano-adsorbents are crucial for their practical applications, especially in industrial processes. Nano-adsorbents can be improved by enhancing their thermal, chemical, and mechanical stability, ensuring that they can be reused multiple times without significant degradation. For instance, modifying the material to resist oxidation, fouling, or degradation in harsh environments (such as high temperatures or corrosive atmospheres) can extend the lifespan of nano-adsorbents, making them more economically viable (Reza et al., 2023). Reusability also reduces waste and environmental impact.

Hybrid Materials
Combining nano-adsorbents with other materials can enhance their performance through synergistic effects. Hybrid materials, such as combining metal-organic frameworks (MOFs) with carbon nanotubes or graphene, can improve adsorption capacity, stability, and selectivity. These hybrid materials can leverage the advantages of different components—such as the high surface area of graphene and the tunable pore structure of MOFs—to create superior adsorbents (Kumar et al., 2024). This can also allow for better control over adsorption properties, making the materials more versatile.

Green Synthesis and Eco-Friendly Materials
A major area of improvement for nano-adsorbents is in their synthesis process. Developing eco-friendly and sustainable methods for producing nano-adsorbents is important for reducing the environmental footprint of these materials. Green synthesis techniques, which use non-toxic solvents, renewable precursors, and energy-efficient methods, can help minimize the negative environmental impact of nano-adsorbent production (Palit & Hussain, 2020). Additionally, using biodegradable or renewable materials to create nano-adsorbents can enhance sustainability.

Optimizing Regeneration Techniques
For nano-adsorbents used in gas capture applications, such as CO_2 removal, improving regeneration methods is critical for increasing efficiency. The ability to regenerate nano-adsorbents without losing performance is important for continuous industrial processes. Developing low-energy or non-thermal regeneration methods, such as chemical or pressure-swing adsorption, can improve the sustainability of nano-adsorbent use, making it more feasible for large-scale applications (Adegoke et al., 2023).

Computational Design and Machine Learning

The use of computational tools and machine learning algorithms can significantly accelerate the development of nano-adsorbents by predicting optimal material properties and configurations. Computational modeling allows researchers to simulate how different nano-adsorbents will behave in various environments and under different conditions, saving time and resources in the material development process (Arshi et al., 2024). Machine learning can be used to analyze vast amounts of experimental data, identifying patterns and guiding the design of more efficient nano-adsorbents.

Nano-adsorbents hold tremendous potential for addressing environmental challenges such as carbon capture and pollution removal. By improving surface functionalization, increasing surface area, enhancing stability, developing hybrid materials, and optimizing regeneration techniques, nano-adsorbents can become even more efficient and practical for large-scale applications. Furthermore, embracing green synthesis methods and utilizing computational tools can streamline the development of advanced nano-adsorbents that are sustainable and effective in mitigating environmental impacts.

Conclusions

This study reveals that the current engineering curriculum is still lagging behind in adopting nano-adsorbent technology as a solution in carbon capture and storage (CCS). Although students and lecturers are aware of the importance of this technology in climate change mitigation, limitations in the curriculum and learning facilities are the main obstacles to its implementation. Practically, the results of this study highlight the urgency of engineering curriculum reform, by incorporating nano-adsorbent materials through theoretical modules, laboratory experiments, and industrial applications. Increased experiential learning is also needed to provide students with more access to laboratories and industrial internships. In addition, collaboration between academia and industry is essential to bridge the gap in students' practical understanding of CCS technology.

Academically, this research contributes by identifying gaps in engineering education and offering concrete strategies for integrating nano-adsorbent technology in the curriculum. In addition, the results of this study open up opportunities for further studies, including the trial of nano-adsorbent-based curriculum, long-term impact analysis, and exploration of educational policies to encourage the implementation of this technology. In conclusion, engineering curriculum reform must be carried out immediately so that graduates have sufficient understanding and skills in CCS and nano-adsorbent technology. The integration of these technologies in engineering education will improve the readiness of graduates in green industries as well as contribute to global efforts in climate change mitigation through sustainability technologies.

References

Adegoke, K. A., Giwa, S. O., Adegoke, O. R., & Maxakato, N. W. (2023). Bibliometric evaluation of nanoadsorbents for wastewater treatment and way forward in nanotechnology for clean water sustainability. *Scientific African*, *21*, e01753.

Alrbaihat, M. R. (2024). *Carbon Capture by Carbonaceous Materials and Nanomaterials*.

Altalhi, T., & Mazumder, M. A. J. (2023). *Green Sustainable Process for Chemical and Environmental Engineering and Science: Applications of Advanced Nanostructured Materials in Wastewater Remediation*. Elsevier.

Aravind, J., & Kamaraj, M. (2024). *Carbon-based Composites and Nanocomposites: Adsorbents and Membranes for Environmental Remediation*. Walter de Gruyter GmbH & Co KG.

Arshi, O., Gupta, S. K., & Mondal, S. (2024). Nano-Technological Interventions for the Sustainable Management of Industrial Solid and Liquid Waste. *Nanotechnology for Environmental Management*, 49.

Bhattacharjee, S., Girigoswami, A., Nag, M., Rubab, T., & Girigoswami, K. (2024). Role of nanotechnology as a zero waste tool. *Environmental Quality Management*, *33*(4), 193–209.

Boell, S. K., & Cecez-Kecmanovic, D. (2015). On being 'systematic' in literature reviews. *Formulating Research Methods for Information Systems: Volume 2*, 48–78.
Bryman, A. (2016). *Social research methods*. Oxford university press.
Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
Firdaus, R. M., Desforges, A., Mohamed, A. R., & Vigolo, B. (2021). Progress in adsorption capacity of nanomaterials for carbon dioxide capture: A comparative study. *Journal of Cleaner Production*, *328*, 129553.
Haghi, A. K., & Thomas, S. (2015). *Carbon Nanotubes: Theoretical Concepts and Research Strategies for Engineers*. CRC Press.
Hussain, C. M. (2020). *The ELSI Handbook of Nanotechnology*.
Jensen, J. L., Karell, D., Tanigawa-Lau, C., Habash, N., Oudah, M., & Fairus Shofia Fani, D. (2022). Language models in sociological research: An application to classifying large administrative data and measuring religiosity. *Sociological Methodology*, *52*(1), 30–52.
Koduru, J. R., Karri, R. R., & Mubarak, N. M. (2023). *Hybrid Nanomaterials for Sustainable Applications: Case Studies and Applications*. Elsevier.
Kumar, A., Indhur, R., Sheik, A. G., Krishna, S. B. N., Kumari, S., & Bux, F. (2024). A review on conventional and novel adsorbents to boost the sorption capacity of heavy metals: current status, challenges and future outlook. *Environmental Technology Reviews*, *13*(1), 521–543.
Mazari, S. A., Mubarak, N. M., & Tripathi, M. (2022). *Nanomaterials for Carbon Dioxide Capture and Conversion Technologies*. Elsevier.
Mills, D., & Ratcliffe, R. (2012). After method? Ethnography in the knowledge economy. *Qualitative Research*, *12*(2), 147–164.
Moleong, L. J. (2000). Qualitative Research Methodology, Bandung: PT. *Youth Rosdakarya*.
Nassar, N. N., & Hussain, C. M. (2023). *Nanoremediation: Modern Technologies for Treatment of Environmental Pollutants*. Elsevier.
Nazir, R. (2018). *Nanotechnology applications in environmental engineering*. IGI Global.
Nguyen, K.-H., Comans, T., Nguyen, T. T., Simpson, D., Woods, L., Wright, C., Green, D., McNeil, K., & Sullivan, C. (2024). Cashing in: cost-benefit analysis framework for digital hospitals. *BMC Health Services Research*, *24*(1), 694.
Nworie, F. S. (2024). Development of Nano-adsorbent for Heavy Metals Removal from Wastewater. In *Heavy Metal Toxicity: Human Health Impact and Mitigation Strategies* (pp. 265–292). Springer.
Palit, S. (2018). Environmental Engineering Applications of Carbon Nanotubes: A Critical Overview and a Vision for the Future. *Engineered Carbon Nanotubes and Nanofibrous Material*, 101–126.
Palit, S., & Hussain, C. M. (2020). Nanomaterials for environmental engineering and energy applications. *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*, 1–24.
Penchah, H. R., & Maleki, F. (2024). Polymeric adsorbents for gas adsorption. In *Polymeric Adsorbents* (pp. 205–258). Elsevier.
Prabhu, S. M., Rane, N. R., Li, X., Otari, S. V, Girawale, S. D., Palake, A. R., Kodam, K. M., Park, Y.-K., Ha, Y.-H., & Yadav, K. K. (2023). Magnetic nanostructured adsorbents for water treatment: Structure-property relationships, chemistry of interactions, and lab-to-industry integration. *Chemical Engineering Journal*, *468*, 143474.
Prasad, R. T., & Gupta, J. (2024). Recent Advances in the Application of Nanomaterials for Environmental Sustainability. *Hybrid Composite Materials: Experimental and Theoretical Analysis*, 333–348.
Reza, M. S., Afroze, S., Kuterbekov, K., Kabyshev, A., Zh. Bekmyrza, K., Haque, M. N., Islam, S. N., Hossain, M. A., Hassan, M., & Roy, H. (2023). Advanced applications of carbonaceous materials in sustainable water treatment, energy storage, and CO2 capture: a comprehensive review. *Sustainability*, *15*(11), 8815.
Sarkodie, B., Tawiah, B., & Fei, B. (2024). Nanotechnology and the Environment: Opportunities and Challenges. *Nanotechnology in Societal Development*, 191–228.
Sen, P., Bhattacharya, P., Mukherjee, G., Ganguly, J., Marik, B., Thapliyal, D., Verma, S., Verros, G. D., Chauhan, M. S., & Arya, R. K. (2023). Advancements in doping strategies for enhanced photocatalysts and adsorbents in environmental remediation. *Technologies*, *11*(5), 144.
Shukla, S., Khan, R., & Hussain, C. M. (2020). *Nanoremediation*.

Sugiyono, D. (2013). *Educational research methods approach quantitative, qualitative and R&D*. Bandung: Alfabeta.

Suharsaputra, U. (2012). Quantitative, Qualitative, and Action Research Methods. *Bandung: PT. Refika Aditama*.

Tawiah, B., Abraham, A. M., & Kappen, J. J. (2024). Nanotechnology and Water: Emerging. *Nanotechnology in Societal Development*, 333.

Tawiah, B., Abraham, A. M., Kappen, J. J., Raju, N. M., Rajan, C. S., & George, S. C. (2024). Nanotechnology and Water: Emerging Solutions for a Global Crisis. In *Nanotechnology in Societal Development* (pp. 333–374). Springer.

Taylor, S. J., Bogdan, R., & DeVault, M. (2015). *Introduction to qualitative research methods: A guidebook and resource*. John Wiley & Sons.

Verma, C., Aslam, J., & Khan, M. E. (2023). *Adsorption Through Advanced Nanoscale Materials: Applications in Environmental Remediation*. Elsevier.