HIGH SCHOOL EDITION
Journal of Student Research
Volume 13 Issue 4 (2024)

Unlocking the Potential of Nanotechnology for "Terraforming" Mars

Rahul Katari[1], Kristina Lilova[#] and Jothsna Kethar[#]

[1]MLK High School, USA
[#]Advisor

ABSTRACT

Mars exploration has ignited an essential quest to find ways to counter its harsh and inhabitable environment. Among the solutions being explored, nanotechnology emerges as a promising approach, offering innovative techniques to convert the planet's abundant carbon dioxide into oxygen, a crucial element for sustaining life. This research paper dives deeply into the application of nanotechnology for the potential terraforming of Mars and examines its viability in supporting human colonization. It provides a comprehensive review of recent breakthroughs in oxygen production technologies, such as plasma technology, NASA's MOXIE experiment, and pioneering techniques involving nanocatalysts and ceramic oxygen generators. These advancements are critical for establishing a sustainable environment on Mars, where oxygen production is a necessity for any long-term human presence. Furthermore, the paper highlights the significance of carbon capture technologies in converting CO2 into oxygen, discussing various methods like post-combustion, pre-combustion, oxy-fuel combustion capture, and carbon capture from industrial processes. Each method is analyzed for its relevance and effectiveness in the Martian context. The study underscores the transformative potential of nanotechnology in overcoming the fundamental challenges of oxygen production and environmental sustainability, making the dream of human life on Mars a tangible possibility. By encouraging interdisciplinary research and collaboration, nanotechnology could pave the way for Mars to evolve into a habitable planet, significantly advancing humanity's exploration and cosmic colonization.

Introduction

The prospect of traveling to Mars has started widespread discourse, yet one of the foremost challenges in this endeavor revolves around the suitability of the Martian atmosphere for human survival. However, this obstacle may be resolved through the remarkable capabilities of nanotechnology. By harnessing the power of nanotechnology, the potential exists to transform carbon dioxide chemically, which is approximately 95% of the Martian atmosphere, into life-sustaining oxygen molecules. This transformative process holds promise in rendering the Martian atmosphere more akin to ours. Yet, the pivotal question remains: Is this feat even possible given the current state of technology?

Although initially unexplored, a collaborative effort between scientists and professors from prestigious institutions such as the University of Lisbon, the Dutch Institute for Fundamental Energy Research, Eindhoven University of Technology, Sorbonne University, and MIT, embarked on a groundbreaking project to convert CO2 into O2. Motivated by oxygen's crucial role in fostering a breathable environment and its potential as a precursor for Martian agriculture, these experts sought to pioneer a method based on plasma technology. Vasco Guerra, a leading author from the University of Lisbon, highlighted the formidable challenges involved in this endeavor, including the intricate process of decomposing CO2 molecules to extract oxygen and subsequently separating it from other gasses like carbon dioxide and carbon monoxide. By approaching these obstacles holistically and harnessing the power of plasmas, the team aimed to revolutionize both steps simultaneously. The outcome of their experiment yielded promising results, suggesting a viable pathway towards sustaining life on Mars and potentially mitigating climate change on Earth. This innovative approach not only addresses the pressing need for oxygen production in extraterrestrial environments but also holds promise as a sustainable solution to environmental challenges here on our home planet (American Institute of Physics, 2022).

In a remarkable feat of engineering, NASA developed a cutting-edge robot known as MOXIE, short for Mars Oxygen In-Situ Resource Utilization Experiment, with the groundbreaking capability to transform carbon dioxide into oxygen. Two days before Earth Day in 2021, MOXIE made history by releasing approximately 5.4 grams of oxygen into the thin Martian atmosphere. Functioning by ingesting carbon dioxide and subsequently generating oxygen, MOXIE represents a pivotal step towards facilitating human exploration of Mars. This innovation addresses the critical challenge posed by Mars's atmosphere, which is composed predominantly of carbon dioxide, with oxygen levels that are mere fractions of what is necessary for human survival. However, despite its groundbreaking potential, MOXIE's energy-intensive operation presents a significant challenge to its widespread application. The substantial energy requirements associated with converting CO2 to O2 raise questions about the long-term viability and scalability of this method. As researchers continue to refine MOXIE and explore alternative approaches, the quest for sustainable oxygen production on Mars remains an ongoing endeavor at the forefront of space exploration (NASA, n.d.).

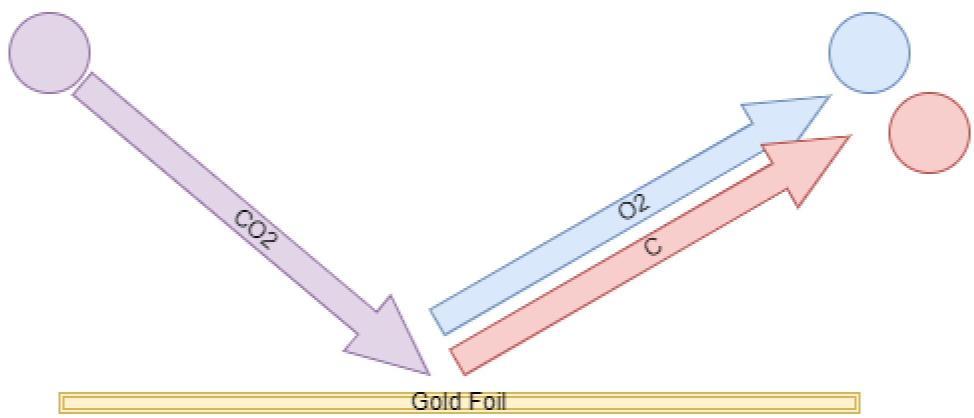

Figure 1. Caltech Experiment**.** Description: The figure above shows how Caltech's experiment was done. Source: Katari, 2024

Located in the heart of California, Caltech, officially known as the California Institute of Technology, stands as one of the most esteemed educational institutions in the state. Within its renowned halls, Konstantinos P. Giapis and Tom Miller, distinguished professors of chemical engineering and chemistry, embarked on a groundbreaking journey to convert carbon dioxide into oxygen. Their innovative approach unveiled a surprising solution nestled within the delicate confines of gold foil. Giapis's ingenious apparatus, crafted to organize this groundbreaking reaction, operates like a particle accelerator, although at significantly lower energies than its counterparts. Within this marvel of scientific ingenuity, CO2 molecules undergo a transformative journey, infused with electric charge and propelled forward by an electric field. While the resemblance to a particle accelerator is striking, Giapis is quick to note that such imposing machinery is not a prerequisite for catalyzing this remarkable reaction. In his vision, the essence of this process transcends the need for extravagant equipment, highlighting the elegance and simplicity underlying the fundamental principles at play. Through Giapis's innovative design, the boundaries of possibility are pushed ever further, offering a glimpse into a future where sustainable solutions are within reach, even with modest means (Velasco, 2019).

Exploring this subject matter is crucial as it holds the potential to unlock the doors to Martian colonization. A significant obstacle in establishing a viable habitat on Mars lies in the scarcity of oxygen, an essential element for human sustenance. Leveraging the power of nanotechnology, we can revolutionize the conversion process by tapping into the abundant resource of carbon dioxide present in the Martian atmosphere, ultimately transforming it into life-sustaining oxygen. This breakthrough not only addresses a fundamental challenge but also paves the way for sustainable human presence on the Red Planet.

Methodology

The methodology for the secondary literature review on "Unlocking the Potential of Nanotechnology for Terraforming Mars" involved a systematic approach to gathering, selecting, synthesizing, and analyzing relevant literature. The process commenced with a comprehensive search across various academic databases and repositories, utilizing specific keywords related to nanotechnology, Mars, terraforming, oxygen generation, and carbon capture. The inclusion and exclusion criteria were established to ensure the selection of credible and relevant sources. Subsequently, the identified literature underwent rigorous screening based on its direct significance to nanotechnology's role in oxygen generation and carbon capture for Mars terraforming. Following the selection process, data extraction and synthesis were conducted to organize the extracted information into thematic categories. This facilitated the identification of patterns, trends, and gaps in the literature, enabling a comprehensive understanding of the current state of knowledge in the field. Critical analysis was then applied to assess the quality and reliability of the selected sources, considering factors such as experimental methodology, theoretical frameworks, and peer-reviewed status. Integration and interpretation of the synthesized information were pivotal in constructing a coherent narrative outlining the potential of nanotechnology for facilitating human exploration and colonization of Mars. The review was structured following a predefined outline, with clear documentation and citation of all referenced literature sources to ensure transparency and reproducibility. Through this systematic approach, the methodology aimed to provide valuable insights into the transformative potential of nanotechnology in addressing fundamental challenges such as oxygen production and environmental sustainability for Mars terraforming. By adhering to rigorous research standards and methodologies, the review sought to contribute meaningfully to the ongoing discourse on the feasibility and implications of leveraging nanotechnology for terraforming Mars and advancing humanity's interplanetary exploration endeavors.

The Idea of Terraforming Mars

Terraforming Mars entails transforming its harsh environment into one hospitable for human life. Currently, Mars has a thin atmosphere, lacks a magnetic field, and has extreme temperatures making it difficult to terraform. However, with advancing technology and resources, this transformation is feasible. Though long explored in science fiction, terraforming Mars is now within reach due to technological advancements. The process involves thickening the atmosphere, creating a magnetic field, and introducing water and vegetation to mirror Earth's ecosystem. The benefits of terraforming Mars are vast, offering a backup for Earth in case of disaster, opening avenues for exploration, and establishing human colonies. However, its feasibility sparks debate due to cost and environmental risks. Technological advances play a crucial role in terraforming. Solutions like changing the atmospheric composition through greenhouse gas emissions, water generation from underground sources, and energy generation through solar panels or nuclear fusion are key. Ecological challenges pose obstacles to Mars colonization. Issues like soil quality, water management, food production, waste management, and biodiversity preservation demand innovative solutions. Ethical considerations are crucial in terraforming and colonization efforts. Environmental impact, social justice, economic viability, and labor rights must be carefully addressed. The future of humanity relies on interplanetary travel, colonization efforts, and terraforming beyond Mars. Developing new propulsion technologies, creating space habitats, and exploring other planets and moons are vital steps in this journey. While the timeline for terraforming Mars spans centuries, ongoing research and development bring humanity closer to realizing this monumental endeavor (Space Mesmerise, n.d.).

Future of Space Colonization: Terraforming vs. Habitats

An article explores whether the future of space colonization lies in terraforming planets like Mars or in developing self-sustaining habitats. It weighs the challenges and benefits of each approach, discussing technological, ethical, and logistical considerations. Looking at the various methods to colonize Mars is crucial to finding the most efficient way (Williams, 2017).

Sustainable Terraforming Methods

Research was conducted focusing on sustainable methods for terraforming Mars. It highlights the importance of ecological and technological sustainability in transforming Mars' environment to support human life, proposing various innovative techniques and approaches. This research talks about air quality, paraterraforming domes, etc. (Wong, 2018).

Is Terraforming Worth It?

Two papers presented at NASA's "Planetary Science Vision 2050 Workshop" explore the concept of terraforming Mars and offer alternative perspectives on humanity's future in space. "The Terraforming Timeline" outlines a plan to transform Mars into a habitable planet, divided into warming and oxygenation phases, which could take up to 100 years and 100,000 years respectively. The authors propose investigating Martian resources and addressing ethical dilemmas before initiating terraforming. They argue that the process, though challenging, is feasible with technological advancements.

Contrarily, "Mars Terraforming – the Wrong Way" suggests focusing on space habitats in low Earth orbit (LEO) instead of planetary colonization. The author highlights the dangers of settling on celestial bodies like Mars due to radiation exposure and low gravity's adverse effects on human health. He advocates for creating biospheres in LEO, utilizing artificial gravity and robotic resource extraction, as a safer and more efficient alternative. This approach could facilitate gradual space colonization and crucial research while reducing risks and costs associated with terraforming (Williams, 2017).

The debate between terraforming Mars and establishing space habitats reflects diverse visions for humanity's space exploration future. While some prioritize transforming planets into new habitable environments, others advocate for safer and more manageable alternatives like space habitats. With advancements in technology and the growing interest of government agencies and private companies in space exploration, humanity may witness various approaches to space colonization in the coming decades. (Williams, 2017).

Terraforming and Nanotechnology

Terraforming Mars is undeniably a formidable challenge, but advancements in nanotechnology offer promising solutions. By harnessing the power of nanocatalysts and other nanotechnologies, the daunting task of transforming Mars into a habitable environment could become significantly more feasible. These technologies could accelerate atmospheric modification, making the vision of a terraformed Mars more attainable. Exploring how nanomaterials and nanotechnology could alter the Martian environment, potentially makes the planet more habitable for humans through advanced and efficient technological solutions.

Converting CO2 to O2 Using Nanotechnology

Research has demonstrated the potential of a COG (ceramic oxygen generators) cell, in front of a CCDL (catalytic carbon deposition layer), for the complete conversion of CO2 into O2 and solid carbon as shown below.

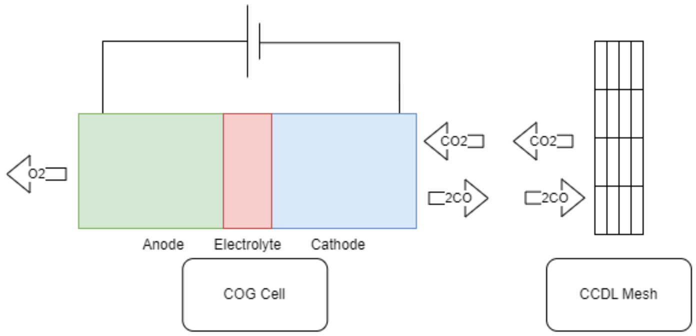

Figure 2. COG cell and CCDL. Description: The figure above is a diagram of the COG cell and CCDL mesh working together to generate oxygen. Source: Katari, 2024

The COG cell efficiently electrochemically extracted oxygen from CO2 gas. In this process, an electric potential is applied across a dense oxide ion-conducting electrolyte, leading to the electro-catalytic reduction of CO2 at the cathode to produce carbon monoxide and oxygen ions like so: $2CO_2 + 4e^- \rightarrow 2CO + 2O^{2-}$.These oxygen ions are then transported to the anode through the electrolyte, where they recombine to form O2 molecules as follows: $2O_2 \rightarrow O_2 + 4e^-$. The overall reaction results in $2CO_2 \rightarrow 2CO + O_2$. The oxygen flux through the COG is determined by Faraday's Law, which relates it to the applied current, power, and voltage, as well as Faraday's constant and the number of electrons transferred during ionization as follows: $J_{o_2} = \frac{i_{app}}{nF} = \frac{P_{app}}{V_{app}nF}$. Conventional COGs typically use yttria-stabilized zirconia electrolytes operating at high temperatures, but newer materials like gadolinium doped ceria (GDC) and erbia-stabilized bismuth oxide (ESB) offer potential benefits at lower temperatures. GDC is stable but prone to electronic conductivity at low oxygen pressures, while ESB is stable but decomposes under similar conditions. To address these challenges, a bilayer electrolyte concept is proposed, where ESB blocks electronic current and GDC protects ESB from low oxygen pressures, such as those encountered with CO. Despite encountering deviations from Faraday's Law due to processing-induced electrolyte cracks, advancements in processing techniques offer promising solutions to mitigate this issue.

Moreover, the CCDL exhibited notable catalytic activity for carbon deposition, particularly showcasing superior performance with nitrogen dispersed on alumina nanoparticles. Carbon deposition occurred solely on the removable CCDL when utilized alongside the COG cell. (NASA n.d)

Nanotechnology for Carbon Sequestration

CO2 Capture

To convert carbon dioxide to oxygen, we must first capture the carbon dioxide. CO2 capture from various gas streams can be classified into four main processes: post-combustion capture, pre-combustion capture, oxy-fuel combustion capture, and capture from industrial process streams. The selection of the appropriate capture process depends on factors such as the CO2 content in the gas stream, the gas stream pressure, and the type of fuel used (whether solid or gas). Consequently, not all capture processes are compatible with all systems. However, all these processes involve separating CO2, O2, or H2 from a gas stream, such as flue gas, air, natural gas, or biogas. This separation can be achieved using various methods including physical or chemical solvents, solid sorbents, membranes, cryogenic separation, or combinations of these techniques. Each CO2 capture process offers distinct advantages and disadvantages.

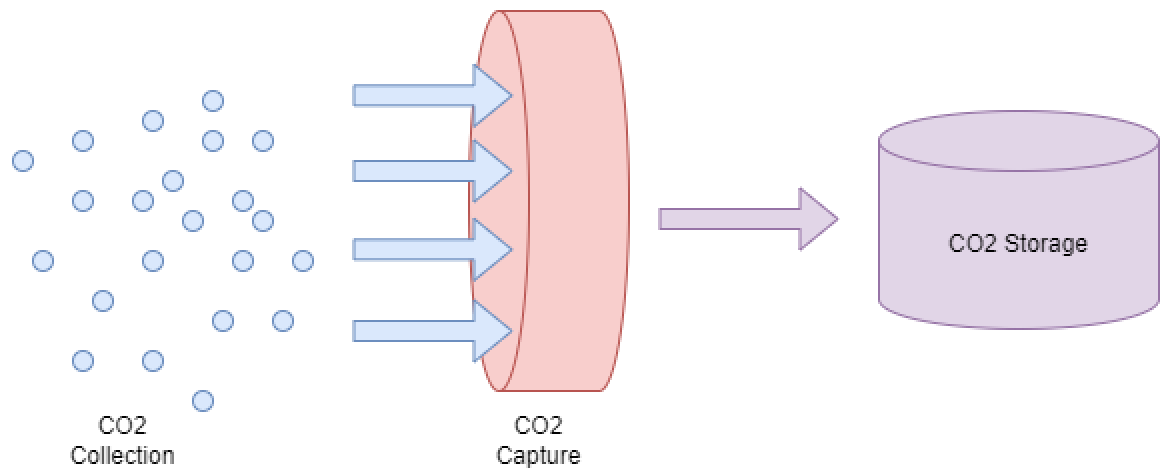

Figure 3. Carbon Capture. Description: This diagram shows the basics of how carbon capturing works.
Source: Katari, 2024

Post-combustion capture, for instance, facilitates the retrofitting of existing plants, enabling an immediate reduction in emissions. However, inefficient capture is due to the low partial pressure of CO2 and the presence of impurities that degrade the solvents used is a major flaw. On the other hand, an advantage of pre-combustion capture is the high partial pressure of CO2 and concentrated gas streams, which leads to efficient absorption and reduced solvent consumption. Nonetheless, it entails the challenge of gasification, which increases process cost and complexity. In oxy-fuel capture, burning fuel with high-purity oxygen generates a concentrated CO2 stream conducive to absorption. However, the energy-intensive air separation process required for oxy-fuel combustion poses a significant drawback.

CO2 capture can be efficiently achieved through physical and chemical adsorption at room temperature and atmospheric pressure. The captured CO2 can be easily released using gas flow and heating methods, or through moisture-swing adsorption by controlling humidity levels.

The effectiveness of physical adsorption (the process of atoms, ions or molecules from a substance adhering to the surface of another material) using nanomaterials largely depends on factors like surface area, porosity, diffusion path, and availability of adsorption sites. Extensive research has led to the development of various nanomaterials with strong CO2 adsorption capabilities, including activated carbon, zeolites, metal-organic frameworks (MOFs), boron nitride (BN), and MXenes (two-dimensional inorganic compounds) (Segneri et al., 2023)

Activated carbon is known for its high surface area, large porosity, and good thermal and chemical stability, making it cost-effective and readily available. Its porosity and surface area can be tailored through pyrolysis and etching methods. However, the efficiency of activated carbon is limited by weak interactions between CO2 molecules and the material (Coromina et al., 2015).

Zeolites offer stronger interactions between CO2 molecules and their negatively charged surfaces. Their high surface area and porosity, combined with adjustable aluminum and silicon ratios, enhance CO2 capture efficiency. Zeolites' adsorption properties can be regenerated through heating, but their high water sorption capacity limits their use in humid environments (Yu et al., 2014).

MOFs (Metal Organic Frameworks) are hybrid crystalline materials formed from metal cations and organic ligands, featuring customizable pore sizes and high surface areas. ZIF-8, a type of MOF, is notable for its chemical and thermal stability and high CO2 adsorption capacity. Conjugated microporous polymers (CMPs) have shown even higher CO2 sorption capacity due to optimized pore size distribution (Cai et al., 2020).

Nano boron nitride (BN) nanomaterials can control CO2 capture and release through charge manipulation. They exhibit strong adsorption when charged and weak adsorption when uncharged, making them highly selective and reversible. BN composite foams, created with poly(vinyl alcohol), enhance CO2 uptake due to improved porosity and mechanical properties (Sun et al., 2013).

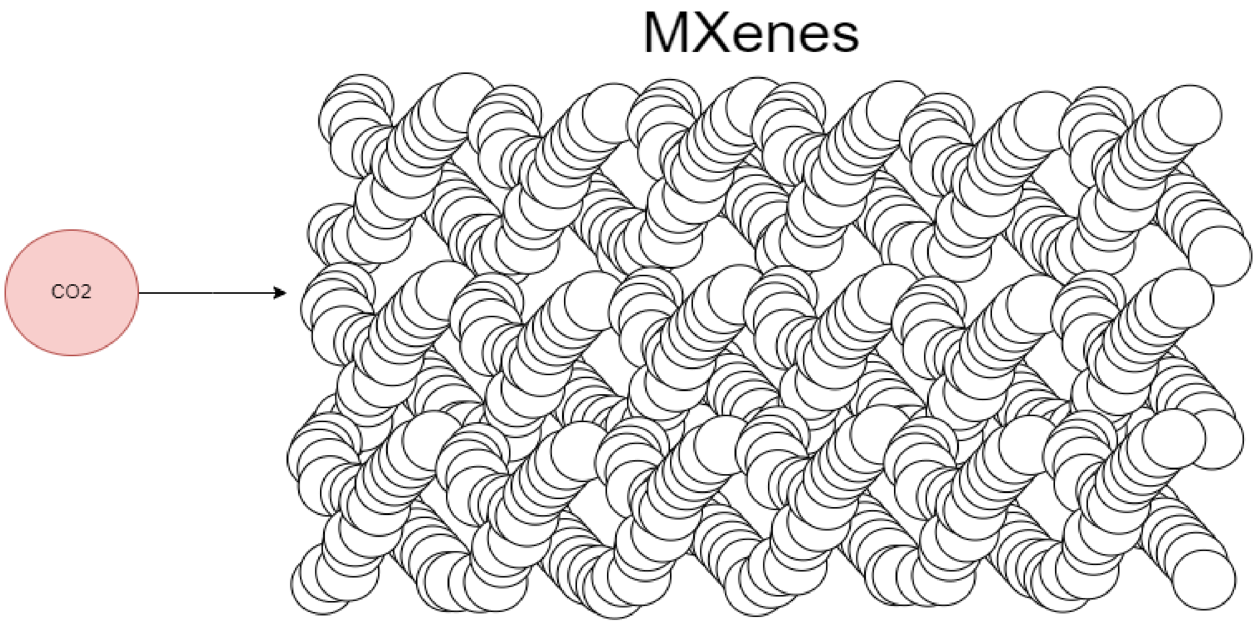

Figure 4. MXenes and CO2. Description: The figure above is a diagram of MXenes interacting with CO2. Source: Katari, 2024

MXenes, particularly from the groups' IV to VI series, are promising for CO2 physical adsorption and selective conversion to CH4. These materials facilitate the formation of radical species necessary for CO2 reduction to hydrocarbons, providing insights into the electrochemical mechanisms of CO2 fixation.

These advanced nanomaterials show significant potential for efficient CO2 capture, each with unique properties that can be optimized for various applications (Li et al., 2017).

Post-Combustion Capture

Post-combustion capture involves separating CO2 from flue gases generated after the combustion of fossil fuels or biomass. Typically, these gases exhibit low CO2 content (3–20%), low partial pressure of CO2 (0.03–0.2 bar), and high temperatures (120–180 °C), while containing NOx and SOx impurities. During this process, flue gas is diverted to specialized equipment designed to extract a significant portion of the CO2. The separated CO2 is then directed to storage, while the remaining flue gas is released into the atmosphere. Additionally, carbon capture from various industries, such as cement and stainless-steel manufacturing facilities, can also be categorized as post-combustion capture, often yielding higher CO2 concentrations compared to typical flue gases. Chemical absorption, utilizing aqueous amine solutions, stands as the most commonly applied method for post-combustion capture.

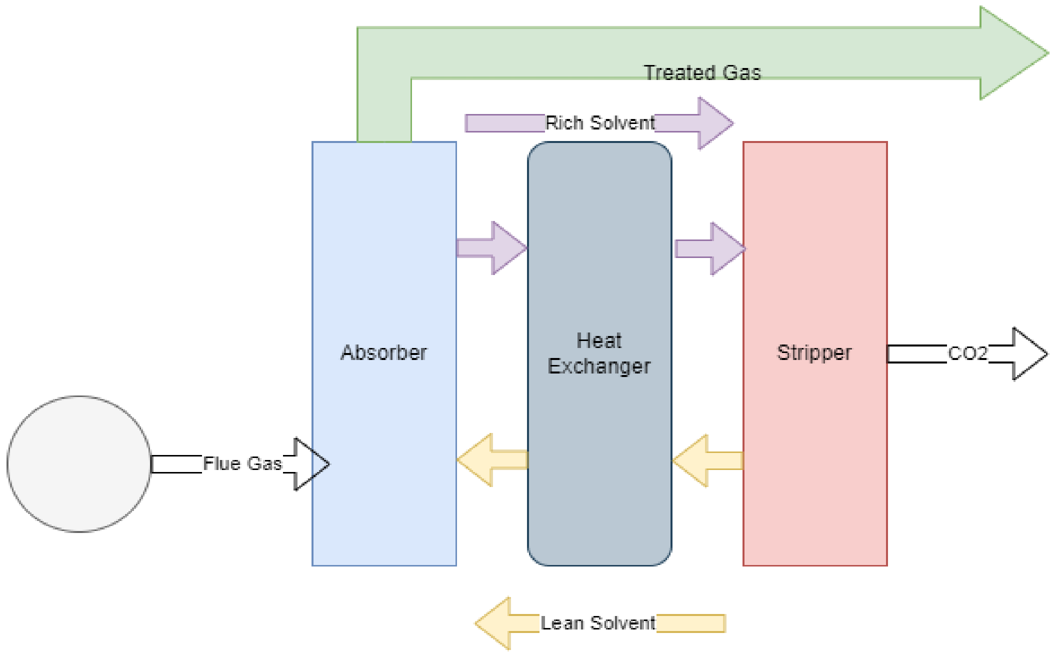

Figure 5. Post Combustion capture diagram. Description: This basic schematic shows how post-combustion capturing works. Source: Katari 2024

Pre-Combustion Capture

Pre-combustion capture involves capturing CO2 from synthesis gas (syngas) following the conversion of CO into CO2. This process commences with the reaction of fuel with O2 (or air) and/or steam, producing primarily synthesis gas or flue gas comprising CO and H2. Subsequently, CO undergoes a water–gas shift reaction (WGS) in a catalytic reactor known as a 'shift converter,' yielding CO2 and additional hydrogen. After the WGS reaction, the flue gas exhibits high CO2 content (15–60% dry basis) at total pressures of 2–7 MPa. Physical solvents like Rectisol or Selexol are commonly employed for CO2 capture in pre-combustion processes. The resulting hydrogen-rich fuel finds utility in heat and power generation applications such as furnaces, boilers, engines, gas turbines, and fuel cells. Typically, most pre-combustion gas streams contain 15–40% CO2 at elevated pressures (200–600 psi).

Oxy-Fuel Combustion Capture

Oxy-fuel combustion capture, initially developed to produce high-purity CO2 (>99%) for enhanced oil recovery (EOR), entails burning fuel with nearly pure oxygen (95–99%) instead of air. This method generates a flue gas rich in H2O and CO2 at very high concentrations. Although using pure oxygen for combustion yields high flame temperatures, CO2 and water-rich flue gas can be recycled in the combustor to mitigate this effect. Cryogenic air separation is commonly employed for oxygen production, although alternative technologies such as membrane separation are also utilized to a lesser extent.

Capture from Industrial Process Streams

Various industrial applications involve process streams that offer opportunities for capturing significant amounts of CO2 at relatively low costs. While capturing CO2 from these sources has been practiced for over 80 years, much of the captured CO2 is typically released into the atmosphere due to a lack of incentives for further utilization or storage.

HIGH SCHOOL EDITION
Journal of Student Research
Volume 13 Issue 4 (2024)

Nevertheless, capturing CO2 from industrial process streams serves as a crucial starting point for initial CO2 capture efforts. Examples include the purification of natural gas and the production of syngas for ammonia, alcohol, and synthetic liquid fuel synthesis. Additionally, industrial processes like fermentation, cement production, and steel manufacturing offer further opportunities for CO2 capture. Some industrial process streams integrate multiple CO2 capture processes, regardless of their CO2 concentration levels. Although using this process for carbon capturing is yet to be possible on Mars, it will be once humans colonize the planet and start using industrial plants (Petros, et al., 2023).

Utilizing Gold Nanocatalysts for Carbon Conversion

There was an investigation conducted looking into the size-dependent behavior of gold nanoparticles (Au NPs) for CO2 electro reduction representing a comprehensive exploration, spanning diameters ranging from 1.5 to 6.5 nanometers. This study not only sheds light on the electrocatalytic properties of Au NPs but also underscores the critical role of accurate nanoparticle characterization techniques in advancing our understanding of catalytic processes.

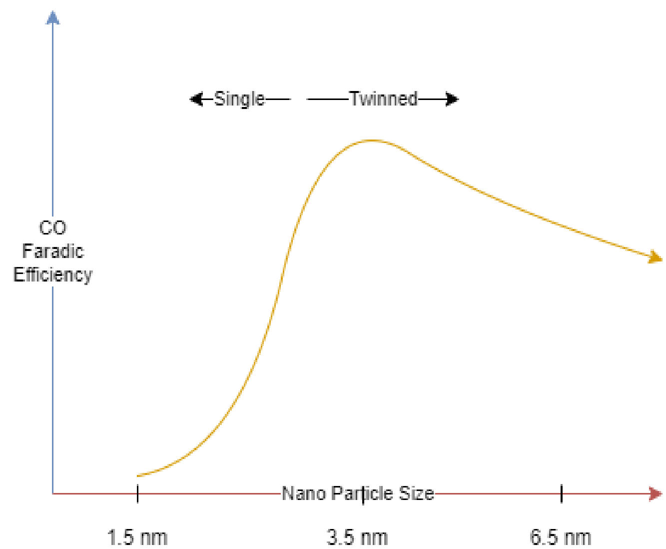

Figure 6. How Nano Particle Size Affects CO Faradic Efficiency. Description: The figure above shows how the size of the nanoparticles can affect the CO Faradic Efficiency and the peak efficiency is around 3.5nm. Source: Varo et al., 2023

Initially, the characterization process involved estimating nanoparticle sizes through a spherical approximation method. However, it became evident that such an approach might not fully capture the intricacies of smaller nanoparticles, particularly regarding their non-spherical shapes. To address this limitation, advanced microscopy techniques such as tapping-mode atomic force microscopy (AFM) and scanning electron microscopy (SEM) were employed. These techniques enabled direct measurements of nanoparticle heights and diameters on graphene-covered substrates, providing a more accurate representation of their dimensions. Discrepancies between estimated and measured sizes highlighted the importance of utilizing precise characterization methods to ensure reliable data interpretation. Electrochemical assessments revealed intriguing size-dependent variations in the selectivity and activity of the Au NPs toward CO2 reduction products. Specifically, nanoparticles with diameters of 2.5 and 3.5 nanometers exhibited enhanced selectivity for carbon monoxide (CO) production, while larger nanoparticles demonstrated a preference for hydrogen (H2) generation. Notably, the smallest nanoparticles (1.5 nanometers) predominantly generated H2, possibly attributed to their unique single crystalline structure. These findings underscore the complexity of size-dependent electrocatalytic behavior and emphasize the need for tailored nanoparticle design to optimize catalytic performance.

Further insights into the atomic structures of the Au NPs were obtained through high-resolution transmission electron microscopy (HRTEM) imaging. The HRTEM images revealed distinct structural features, including single crystalline structures for the smallest nanoparticles and multiple twinned particle (MTP) structures for larger ones. Surface site analysis indicated that MTP structures exposed surface sites conducive to CO selectivity, with a higher fraction of grain boundary sites compared to single crystal structures. This detailed structural analysis explains the correlation between nanoparticle morphology and catalytic activity, providing valuable insights for the rational design of efficient electrocatalysts.

In conclusion, this study underscores the multifaceted interplay between nanoparticle size, shape, and electrocatalytic performance. By employing advanced characterization techniques and rigorous electrochemical assessments, researchers can understand the underlying principles governing nanoparticle behavior and pave the way for the development of highly efficient catalysts for CO2 conversion and other sustainable energy applications. (Varo et al., 2023)

Conclusion

Nanotechnology presents a transformative potential for terraforming Mars, offering innovative solutions to the significant challenges posed by the planet's inhospitable atmosphere. Through advancements in oxygen generation technologies and carbon capture methods, nanotechnology can play a crucial role in converting Mars's abundant carbon dioxide into life-sustaining oxygen.

Nanotechnology also offers advanced materials for CO2 capture, including activated carbon, zeolites, MOFs, boron nitride, and MXenes. These materials, with their high surface areas and customizable properties, enable efficient and selective CO2 adsorption, essential for subsequent conversion processes. Moreover, the integration of ceramic oxygen generators and catalytic carbon deposition layers (CCDL) showcases the feasibility of complete CO2 conversion into oxygen and solid carbon.

The research underscores the importance of interdisciplinary collaboration and continued technological advancements to address the challenges of oxygen production and environmental sustainability on Mars. As the quest for human colonization of Mars progresses, leveraging nanotechnology can significantly enhance the feasibility and efficiency of the terraforming efforts, ultimately bringing humanity closer to realizing the vision of a habitable Mars.

In conclusion, while significant obstacles remain, the advancements in nanotechnology provide a compelling case for its role in terraforming Mars. Through continued research and development, nanotechnology holds the promise of making Mars a viable second home for humanity, advancing our interplanetary exploration and ensuring the sustainability of human presence beyond Earth.

Limitations

This paper specifically focuses on the nanotechnology aspect of terraforming Mars. While there are various methods to terraform a planet like Mars, the objective of this paper is to exclusively explore the potential and application of nanotechnology in this context. Although other methods are briefly mentioned, they are not the primary focus. Given the relative novelty of this topic and its limited exploration in existing literature, there were challenges in finding sufficient related research to support the development of this paper.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

Cai, Z., Bien, C.E., Liu, Q., Wade, C.R., 2020. Insights into CO2Adsorption in M-OH Functionalized MOFs. Chemistry of Materials 32, 4257–4264. https://doi.org/10.1021/acs.chemmater.0c00746

Coromina, H.M., Walsh, D.A., Mokaya, R., 2015. Biomass-derived activated carbon with simultaneously enhanced CO2 uptake for both pre and post-combustion capture applications. J Mater Chem A Mater 4, 280–289. https://doi.org/10.1039/c5ta09202g

Li, N., Chen, X., Ong, W.J., Macfarlane, D.R., Zhao, X., Cheetham, A.K., Sun, C., 2017. Understanding of Electrochemical Mechanisms for CO2 Capture and Conversion into Hydrocarbon Fuels in Transition-Metal Carbides (MXenes). ACS Nano 11, 10825–10833. https://doi.org/10.1021/ACSNANO.7B03738/ASSET/IMAGES/LARGE/NN-2017-03738A_0007.JPEG

Oxygen generation from carbon dioxide for Advanced Life ... (n.d.). https://ntrs.nasa.gov/api/citations/20160008985/downloads/20160008985.pdf

Petros Gkotsis, Effrosyni Peleka, & Anastasios Zouboulis. (2023). Membrane-Based Technologies for Post-Combustion CO2 Capture from Flue Gases: Recent Progress in Commonly Employed Membrane Materials. *Membranes*, *13*(12), 898–898. https://doi.org/10.3390/membranes13120898

Terraforming Mars: The future of human colonization. Space Mesmerise. (n.d.). https://spacemesmerise.com/en-us/blogs/space-exploration/terraforming-mars-the-future-of-human-colonization

Segneria, V., Trincaa, A., Libardib, N., Colellia, L., Micciancioa, M., Vilardia,G. (2023) Nanoparticles used for CO2 Capture by Adsorption: a Review https://www.cetjournal.it/cet/23/101/023.pdf

Sun, Q., Li, Z., Searles, D.J., Chen, Y., Lu, G., Du, A., 2013a. Charge-controlled switchable CO2 capture on boron nitride nanomaterials. J Am Chem Soc 135, 8246–8253. https://doi.org/10.1021/JA400243R/SUPPL_FILE/JA400243R_SI_002.PDF

System engineering analysis of terraforming Mars with an ... (n.d.). https://digitalcommons.lmu.edu/cgi/viewcontent.cgi?article=1890&context=etd

Varo, E. S., Tankard, R. E., Kryger-Baggesen, J., Jinschek, J., Helveg, S., Chorkendorff, I., Damsgaard, C. D., & Kibsgaard, J. (2024). Gold nanoparticles for CO2 electroreduction: an optimum defined by size and shape. *Journal of the American Chemical Society*, *146*(3), 2015–2023. https://doi.org/10.1021/jacs.3c10610

Williams, M. (2017, March 10). The future of space colonization – terraforming or space habitats? *phys.org*. https://phys.org/news/2017-03-future-space-colonization-terraforming-habitats.html

Wong, Brandon, "System Engineering Analysis of Terraforming Mars with an Emphasis on Resource Importation Technology" (2018). LMU/LLS Theses and Dissertations. 888. https://digitalcommons.lmu.edu/etd/888

Yu, Y., Mai, J., Wang, L., Li, X., Jiang, Z., Wang, F., 2014. Ship-in-a-bottle synthesis of amine-functionalized ionic liquids in NaY zeolite for CO2 capture. Sci Rep 4. https://doi.org/10.1038/SREP05997