RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

ESSAY

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Cite this: *RSC Sustainability*, 2024, **2**, 3575

DOI: 10.1039/d4su90045f

rsc.li/rscsus

Chemical innovations in nuclear energy: paving the way for a carbon-neutral future

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There's a 22% probability that 2024 could set a new record as the hottest year in the NOAA's 175-year historical record.[1] This alarming warming trend, exacerbated by escalating carbon emissions, is pushing our planet towards conditions that are increasingly inhospitable for human life and the natural world. The recognition of climate change and global warming dates back to the mid-19th century, notably with the work "Circumstances affecting the heat of the sun's rays" by Eunice Foote, acknowledged as the pioneering climate scientist.[2] This period marked the beginning of a growing awareness about the impact of atmospheric greenhouse gases on Earth's climate. By 2020, human activities, primarily the combustion of fossil fuels for energy generation, contributed to a dramatic increase in atmospheric carbon dioxide levels to approximately 400 parts per million (ppm).[3] Notably, approximately 40% of CO_2 emissions stem from the energy sector,[4] prompting the United Nations to acknowledge the critical need for cleaner and more sustainable energy sources as its 7th goal. In the context of this historical understanding and the substantial rise in greenhouse gas emissions, nuclear energy presents itself as a crucial alternative. Its inherent advantage of producing almost no CO_2 emissions during operations positions nuclear energy as a critical solution for mitigating the primary source of global atmospheric carbon increase, thereby playing a vital role in the efforts to combat climate change.[5] According to the International Atomic Energy Agency (IAEA), nuclear energy usage has cut down carbon emissions by 60 gigatons over 50 years, which is equivalent to nearly two years of worldwide emissions from energy use.[5]

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Sarah is a chemist by training with an Integrated Master's degree from the University of Hyderabad. Her research focuses on materials science and nanotechnology, with experience at institutions like the Indira Gandhi Centre for Atomic Research and the University of Hyderabad. Her interests include nanomaterial synthesis and characterisation, and materials research. Beyond her scientific pursuits, she enjoys quizzing and has held leadership roles in school and university science clubs. Sarah combines her passion for materials research with a commitment to science education and communication.

In the field of nuclear energy generation, chemical sciences play a pivotal role across the entire process. From uranium mining and milling, chemical processes are crucial for extracting and refining uranium from its ore, employing advanced separation and purification techniques including leeching, ion exchange, filtration, and ore sorting.[6] The conversion of uranium into gaseous uranium hexafluoride using wet and dry chemical processes is essential for enrichment, *i.e.*, increasing the concentration of the fissile isotope U-235 in the fuel.[7] Since the chemical properties of both uranium-235 and uranium-238 are identical, the miniscule difference in mass is exploited *via* the technique of diffusion of volatile UF_6 to increase the concentration of uranium-235 in the fuel. Following enrichment, the uranium is processed into fuel pellets by oxidising and then pelletising the enriched uranium into uranium oxide pellets and subjecting it to high temperatures, which converts it into a ceramic material.[8] Furthermore, the chemical sciences contribute to the development of advanced reactors and fuels such as thorium-233 (ref. 9) and plutonium-239 (ref. 10), and the reprocessing of spent nuclear fuel through aqueous and pyrochemical techniques, promoting sustainability and efficiency in nuclear energy production. These steps involve various chemical processes, with the end goal being to recycle spent fuel to extract valuable isotopes, and the synthesis of new forms of fuel that can reduce waste and enhance reactor performance.

Nuclear technology's advantages are not limited to just reducing CO_2 emissions in power generation. It plays a significant role in fields such as agriculture and manufacturing, introducing novel methods and solutions that lead to a reduction in greenhouse gas emissions. For example, in agriculture, nuclear sciences provide solutions aimed at boosting agricultural efficiency and sustainability, thereby reducing the carbon footprint typically linked to traditional farming methods.[11] These advancements draw from the principles of chemistry and nuclear physics, utilising the unique characteristics of isotopes and radiation to tackle fundamental issues in agriculture. A pivotal application of nuclear sciences in agriculture involves utilising gamma radiation, typically from a cobalt-60 source,[12] to generate mutations in crops. These mutations can lead to varieties requiring less water and exhibiting enhanced resistance to pests.[13] This not only alleviates pressure on limited resources by reducing water consumption and enhancing pest control but also diminishes the reliance on pesticides and fertilisers, consequently leading to lower emissions associated with the production of these agricultural inputs. Additionally, the Sterile Insect Technique (SIT) offers an eco-friendly strategy for pest population control by dispersing sterilised insects across specific regions. This method involves large-scale breeding and the sterilisation of target pests through exposure to gamma rays, effectively reducing pest numbers without harmful environmental impacts.[14]

Furthermore, the application of neutron moisture gauges and isotopic tracers, such as nitrogen-15, plays a crucial role in measuring soil moisture and plant nitrogen absorption. These methods utilise the interactions between neutrons or isotopes and the atoms within the soil and plants to shed light on the chemical dynamics of water and nutrient uptake. The strategic use of these nuclear technologies enables the fine-tuning of irrigation schedules and the precise application of fertilizers, significantly conserving water and reducing the excessive use of fertilizers. This approach not only lowers the carbon footprint associated with the production of fertilizers but also curtails the emission of nitrous oxide (N_2O), a potent greenhouse gas emanating from the application of nitrogen-based fertilizers to the soil, further illustrating nuclear science's broad impact on sustainable agriculture.[15]

The integration of chemical sciences with nuclear technology offers transformative approaches to manufacturing, significantly reducing environmental pollution and championing sustainability. One such technique is radiation processing, which utilises ionising radiation for sterilisation and material modification. This technology ensures the safety and efficacy of healthcare products, from bandages to surgical instruments, by sterilising them without heat, maintaining sterility until use. It also mitigates transfusion-related complications, extends the shelf life of food, and enhances agricultural product safety. Additionally, radiation processing contributes to environmental sustainability by treating hospital waste, and purifying industrial emissions.[16,17] These advancements highlight the pivotal role of chemical sciences in leveraging nuclear technology for eco-friendly manufacturing solutions, emphasizing efficiency, sustainability, and the reduction of waste, thereby aligning with cleaner manufacturing principles.

In the battle against climate change, the strategic emphasis on and investment in the chemical sciences, particularly within the domain of nuclear technology, emerges as an avenue we cannot overlook. This interdisciplinary convergence holds the promise of pioneering clean energy alternatives, advancing agricultural methodologies, and bringing about transformative shifts in manufacturing processes. Such endeavours are not merely experimental; they are imperative steps toward addressing the multifaceted challenges posed by climate change, and thereby steering our global community towards a future marked by sustainability, resilience, and prosperity.[18,19] This critical engagement with chemical sciences within the nuclear domain underscores the imperative for collaborative innovation, positioning these fields as quintessential drivers of environmental stewardship and harbingers of a hopeful tomorrow.

The advancements in nuclear technology signify progress towards sustainable nuclear energy utilisation, yet the path is laden with challenges, particularly in handling nuclear waste. Nuclear waste management necessitates meticulous handling and containment to mitigate significant environmental and health risks associated with radioactive waste. The quest for long-term storage and disposal solutions that guarantee safety over geological timescales, especially for liquid waste, remains a challenge. It underscores the need for chemical scientists, using their ingenuity and expertise, to develop innovative strategies that address these challenges, ensuring the responsible and safe management of nuclear waste. This effort aligns with India's proactive approach in reprocessing spent nuclear fuel and vitrifying high-level liquid waste, reflecting a commitment to optimising resource use and minimising waste, while simultaneously extracting valuable isotopes for medical and industrial applications.[20] Nonetheless, the main goal is to create strong waste management systems that prioritise protecting the environment and public health, highlighting the crucial role of scientific innovation in moving us towards a sustainable nuclear future. Additionally, the broader assimilation and endorsement of nuclear energy as a sustainable alternative are hindered by several impediments, including public perceptions, regulatory landscapes, and the substantial initial capital required for the construction of reactors and the establishment of exhaustive safety protocols.[21] These challenges highlight the need for transparent communication, rigorous safety frameworks, and economic viability to facilitate enhanced acceptance and incorporation of nuclear technology into the global energy matrix.

Despite these hurdles, the potential of nuclear technology, augmented by advances in chemical sciences, offers a beacon of hope for mitigating the impacts of climate change. Innovations such as small modular reactors (SMRs)[22] and next-generation nuclear reactors[23] present opportunities for more flexible, safer, and cost-effective nuclear energy solutions. Additionally, the exploration of alternative nuclear fuels and the advancement of fuel reprocessing technologies promise enhanced efficiency and reduced waste, aligning with the goals of sustainability and environmental preservation.

The future welfare of our planet necessitates a forward-looking approach that embraces the challenges and harnesses the potential of nuclear technology. By fostering interdisciplinary collaboration and innovation, investing in research and development, and engaging in dialogue with policymakers, communities, and industries, we can navigate the complexities of nuclear energy. This endeavour is not only about advancing technological capabilities but also about cultivating a societal ethos that values sustainability, equity, and the collective good. The chemical sciences, with their pivotal role in this journey, embody the essence of scientific inquiry and innovation aimed at serving humanity's greatest challenges. As we move forward, it is the spirit of perseverance, collaboration, and visionary leadership that will guide us towards a more sustainable, resilient, and thriving world for future generations.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

AI or AI-assisted technologies were not used to prepare this essay, except for Grammarly for spell-checking and plagiarism detection purposes only.

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