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Empowering Sustainable Development in Afghanistan: Integrating Home Economics and Chemical Engineering

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ABSTRACT

Achieving sustainable development in Afghanistan requires a multidisciplinary approach that integrates social equity, environmental stewardship, and economic growth. This review aims to underscore the fundamental principles of sustainability through the perspectives of home economics and chemical engineering, both of which play vital roles in addressing resource scarcity, reducing reliance on fossil fuels, and promoting sustainability. Home economics fosters community awareness and the adoption of sustainable practices in daily life, emphasizing resource management, nutrition, and waste reduction. Meanwhile, chemical engineering offers innovative solutions in areas such as the hydrogen economy, carbon capture, utilization, and storage (CCUS), biofuels, green chemistry, batteries, energy storage, nuclear energy, and nuclear fusion. Together, these disciplines can drive self-sufficiency and sustainability in Afghanistan's development. As the world shifts from traditional fuels to sustainable alternatives, prioritizing CCUS, renewable energy integration, and resource efficiency becomes essential. A collaborative approach ensures that technological advancements are scalable, economically viable, and culturally adaptable. By combining community education with advanced engineering solutions, this framework empowers Afghan communities and industries in their sustainable transformation, securing resources for present and future generations.

1. INTRODUCTION

Afghanistan is a country endowed with abundant natural resources and a rich cultural heritage, yet it faces significant challenges in achieving sustainable development. These challenges include pervasive poverty, environmental degradation, and inadequate infrastructure. To secure a more sustainable future, Afghanistan must adopt strategies that not only address its immediate development needs but also ensure long-term ecological balance and economic resilience. However, the country has yet to fully benefit from the integration of home economics and chemical engineering due to limited interdisciplinary collaboration, inadequate infrastructure, and insufficient investment in sustainable technologies. The lack of policies promoting resource-efficient practices, coupled with low public awareness of sustainability principles, further impedes progress. Achieving sustainable development in the country requires a comprehensive approach one that bridges the gap between community-driven solutions and technological advancements, integrating grassroots initiatives with large-scale innovations to foster both local empowerment and national progress.

Here, we explore how **home economics**, with its focus on sustainable resource management, nutrition, and environmentally conscious practices, can complement **chemical engineering** in addressing Afghanistan's unique sustainability challenges. **Chemical engineering**, with its expertise in processes and systems, plays a crucial role in transforming natural resources into sustainable solutions. Key areas of **chemical engineering research**, such as hydrogen economy, carbon capture, utilization, and storage (CCUS), biofuels, green chemistry, batteries, energy storage, nuclear energy, and nuclear fusion, offer critical pathways for mitigating environmental impacts and promoting economic growth (Al-Sakkari et al., 2024). Regarding CCS projects, several have been successfully implemented worldwide, including the Sleipner Project in Norway, the Val Verde Natural Gas Plant in the USA, and the Weyburn-Midale Project in Canada. Additionally, multiple large commercial-scale CCS projects for power plants are in various stages of planning or construction in the USA, Canada, Australia, and China (Deployment, n.d.). These innovations provide Afghanistan with opportunities to address pressing issues like energy production, waste management, and resource depletion, while simultaneously creating jobs and fostering the development of sustainable industries.

However, chemical engineering emerged as a distinct discipline to address challenges in chemistry-based separation processes, which traditional mechanical engineers and chemists struggled to comprehend. The formal establishment of chemical engineering as a profession occurred in 1887 in the United Kingdom (Tonkovich & Daymo, 2018), following the creation of the first chemical engineering course by George E. Davis at the University of Manchester. This course focused on various applications of industrial chemistry. The expanding oil and gas sector, particularly the need for natural gas sweetening and crude oil refining to produce fuels such as gasoline for the automobile industry, fueled a global demand for chemical engineers. Between 1960 and 1980, the chemical process industry shifted its focus from developing new products to enhancing process efficiency, using computer-based technologies and computer-aided design (CAD) tools. Concurrently, advancements in computational hardware enabled the application of sophisticated software like computational fluid dynamics (CFD) and advanced process control and optimization techniques (Arastoopour, 2019). By the 1990s, chemical engineers had broadened their expertise to include energy conversion, pharmaceuticals, biotechnology, microelectronics, and nanotechnology. This trend continues to drive innovation and shape the future of chemical engineering research and development.

In contemporary Afghanistan, chemical engineers are increasingly positioned to apply core principles of chemical engineering such as transport phenomena, chemical reaction engineering, process design and scale-up, and advanced experimental techniques and software to play a pivotal role in technology research and development, thereby contributing to the creation of a sustainable future. Their involvement is essential not only in advancing industrial practices but also in leading multidisciplinary research, education, and innovation efforts aimed at fostering a sustainable economy in Afghanistan alongside the global economy. This paper explores both current and emerging research opportunities where chemical engineers can make substantial contributions to sustainability, highlighting their critical role in shaping future technological and industrial landscapes.

The role of chemical engineering research in advancing pathways to a sustainable society; as we know, today, chemical engineers are presented with a unique opportunity to harness advances in experimental measurement techniques and computational tools, including artificial intelligence, neural networks, computational transfer phenomena (CTP), and molecular dynamics. By integrating these technologies with their expertise in systems approaches, chemical engineers can position the field as a leading force in multidisciplinary research and development. This dynamic convergence of innovation and knowledge has the potential to significantly contribute to the development of a sustainable Afghanistan in the future.

As illustrated in Fig. 1, chemical engineers have numerous opportunities to establish themselves as key contributors and leaders in multidisciplinary research and development efforts across several critical areas. Here we focus on the sustainable energy and decarburization: which include hydrogen economy, carbon capture, utilization, and storage (CCUS), biofuels & green chemistry, battery & energy storage, and nuclear energy & fusion.

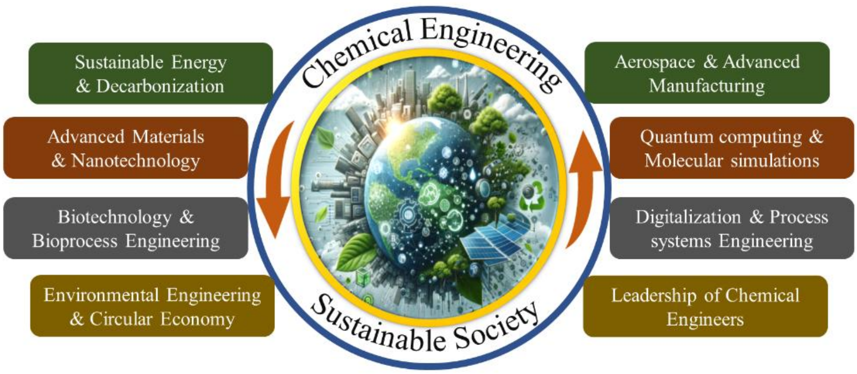

Figure 1: Steps for chemical engineering contribution toward a pathway to sustainability.

2. LITERATURE REVIEW

SUSTAINABLE ENERGY & DECARBONIZATION

Sustainable energy and DE carbonization aim to reduce carbon emissions while ensuring a reliable and clean energy supply. This transition involves shifting from fossil fuels to renewable energy sources, enhancing energy efficiency, and advancing carbon capture technologies. The development of these technologies can create numerous opportunities for industrial growth, research, and education, ultimately fostering job creation and contributing to a more sustainable Afghan society.

2.1 Hydrogen Economy: Development of efficient hydrogen production, storage, and fuel cell technologies.

In its molecular form, hydrogen (H_2) is a lightweight gas that holds one of the highest energy contents per kilogram among all known substances on Earth. However, under standard conditions, its volumetric energy density is only about one-third that of natural gas. Hydrogen is highly flammable, has a rapid flame propagation speed, and burns cleanly without directly emitting greenhouse gases (GHGs), producing only water vapor as a byproduct. Nevertheless, when combusted in the presence of nitrogen, hydrogen can generate nitrogen oxides (NO_x), which are both air pollutants and indirect greenhouse gases. Alternatively, in a fuel cell, hydrogen reacts with oxygen to generate electricity, with water vapor as the sole emission, making it a promising option for sustainable energy applications. The unique chemical and physical properties of hydrogen, combined with its minimal environmental impact, enable its widespread application across various sectors, including power generation, transportation, and industrial processes. Its versatility makes it a key player in the transition to sustainable energy solutions. As shown in Figure 2, the U.S. Department of Energy's H_2@Scale project vision for hydrogen's potential role in a decarbonized economy (Feldmann et al., 2023). However, projections indicate that even by 2050, the hydrogen supply will fall short of the amount needed to fully decarbonize any major sector (IEA 2019a).

The limited availability of hydrogen will necessitate its allocation to applications where it delivers the greatest value. Various factors will shape the supply and demand dynamics of hydrogen, as well as its economic viability across different sectors in both the short and long term. These factors include policy incentives, advancements in production and consumption technologies, project financing, the development of transport and storage infrastructure, and the availability of raw materials and feedstocks. Furthermore, the hydrogen economy presents significant opportunities for Afghanistan's sustainable development, fostering industrial growth, energy security, and environmental sustainability.

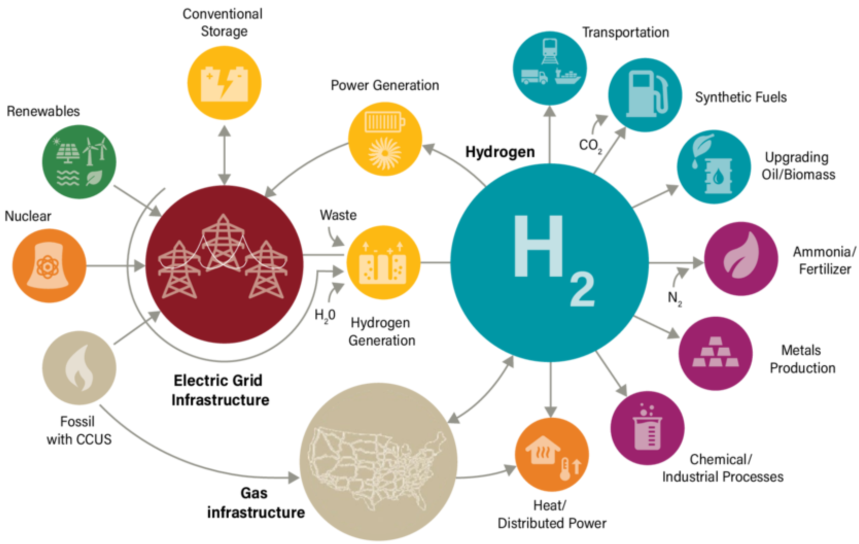

Figure 2: H_2@Scale project vision for hydrogen's potential role in a decarbonized economy.

2.2 Carbon Capture, Utilization, and Storage (CCUS): Designing processes for CO_2 sequestration and conversion into valuable products.

Global energy consumption, excluding coal, is projected to continue increasing until 2050, with renewables emerging as the fastest-growing energy source (Narodoslawsky, 2013). Between 2015 and 2050, renewable energy consumption is expected to rise at an average annual rate of 2.3%. Additionally, diesel fuel consumption has surged, with approximately 94% of freight transportation relying on it due to its higher energy density and superior fuel efficiency (MacDowell et al., 2010; Sun et al., 2019). However, diesel exhaust is a significant source of pollutants, including cytotoxic substances, nitrogen oxides (NO_x), and particulate matter (soot), which adversely affect human health and contribute to substantial climate changes.

One of the primary objectives of the Paris Climate Agreement is to limit global warming to well below 2 °C, with a target to restrict the increase to 1.5 °C, as endorsed at the COP-26 conference, in order to mitigate the impacts of climate change (Iyer et al., 2015). In this context, there is an increasing emphasis on carbon capture, utilization, and storage (CCUS) as a pivotal strategy for decarbonizing the energy and industrial sectors.

CCUS is essential for reducing the greenhouse gas emissions that exacerbate the greenhouse effect and drive global climate change (Callas et al., 2022)

Given these trends, the global emission of CO_2 and its associated climate impacts are expected to persist for the foreseeable future. Chemical engineers, as key professionals in the field, are uniquely positioned to lead the research and development efforts required to advance CO_2 capture, utilization, and sequestration technologies, as shown in Figure 3, the most common approaches and technologies currently used for carbon capture. These efforts present significant opportunities for technological innovation, industrial growth, and job creation, particularly in Afghanistan, where such advancements could support the nation's research, development, and economic prospects.

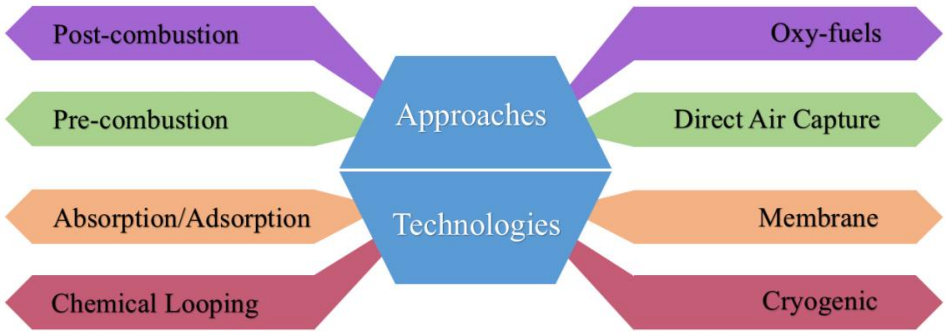

Figure 3. Common carbon capture approaches and technologies.

2.3 Biofuels & Green Chemistry: Developing renewable fuels (e.g., biodiesel, bioethanol, synthetic fuels) and sustainable chemical synthesis.

Current research in chemical engineering, agriculture, and environmental policy focuses on developing clean technologies that maximize the use of sustainable feedstocks. This is particularly important for transportation fuels, which rely heavily on non-renewable petroleum. As petroleum reserves decline, costs increase, making it a less viable carbon source. Additionally, fossil fuel combustion contributes to rising global greenhouse gas emissions. A diversified energy system that incorporates multiple energy sources, rather than relying solely on petroleum, offers a more sustainable long-term solution. Electric, solar, hydrogen fuel cell, and biofuel-powered vehicles are being explored to reduce dependence on oil. However, achieving economic and technical feasibility takes time, and the lack of infrastructure, especially for hydrogen fuel cells, has hampered adoption in markets where liquid hydrocarbons are widely used. In this respect, liquid biofuels derived from plant biomass are similar to conventional fuels and can be used without major infrastructure or engine modifications. Biomass offers a viable short-term alternative for fuel production, with bioethanol and biodiesel already blended into gasoline and diesel (Alonso et al., 2010).

In the petrochemical industry, crude oil is refined into fuels and chemicals. Similarly, biorefining converts renewable biomass into fuels and valuable chemicals within a single facility. Furthermore, in heat and electricity generation, biomass-derived fuels contribute to reducing greenhouse gas emissions through a balanced regeneration and combustion cycle. Biomass feedstocks suitable for renewable fuel production can be classified into three primary categories: starch-based feedstocks (including sugars), triglyceride-based feedstocks, and lignocellulosic feedstocks. Figure 4 shows the various biofuels derived from different biomass feedstocks. Starch-based feedstocks consist of glucose polysaccharides, such as amylose and amylopectin, which are easily hydrolyzed into sugar monomers for processing in first-generation bioethanol facilities. Triglyceride feedstocks consist of fatty acids and glycerol from plants and animals, including vegetable oils, waste oils (such as yellow fat and hydrophobic valve fats), and algae-derived lipids used in biodiesel production. Lignocellulosic biomass, the most abundant feedstock, provides structural integrity to plants and is ubiquitous. It includes energy crops (such as switchgrass and miscanthus), agricultural residues, municipal waste, and wood-processing by-products. Lignocellulose comprises three major components: lignin, hemicellulose, and cellulose (Huber & Corma, 2007). Given that more than 80% of Afghanistan's population depends on agriculture for their livelihood, investing in standardized agricultural practices will significantly contribute to the sustainable development of Afghanistan's economy and education sectors.

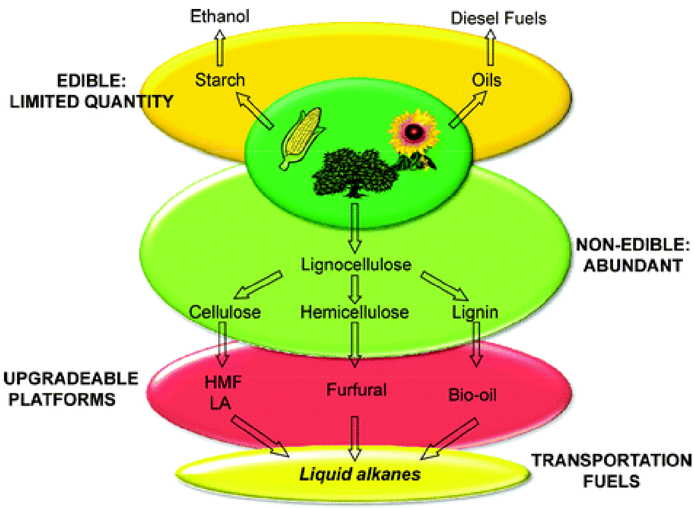

Figure 4. Biomass-derived feedstocks and platforms for conversion to biofuels.

2.4 Battery & Energy Storage: Advancing lithium-ion, solid-state, and flow batteries for improved energy storage

Rising fossil fuel consumption drives pollution and climate change, increasing the demand for clean energy storage. The United States Advanced Battery Consortium (USABC) sets battery standards for EVs, HEVs, and PHEVs based on specific energy and power (Figure 5a). Current Li-ion cells, with a specific energy of 200 W h/kg, barely meet HEV and PHEV needs and fall short of future EV goals, which require a 500-mile range per charge (Srinivasan, 2011). In contrast, Li-S batteries have gained attention for their high theoretical specific capacity of 1675 mA h/g—the highest among known solid cathode materials. Compared to traditional lithium-ion batteries, Li//S batteries offer higher energy density and lower cost. Assuming a complete reaction with Li2S, their theoretical energy density reaches 2500 W h/kg and 2800 W h/L by weight and volume, respectively (Figure 5b). Additionally, sulfur is abundant, inexpensive, and non-toxic. Despite their advantages, Li//S batteries face significant fabrication challenges.

First, both sulfur and its reduction product (Li_2S) are highly insulating, limiting electrochemical accessibility and sulfur utilization. Once a Li_2S layer fully coats the electrode, further lithiation is hindered, causing a rapid voltage drop, making complete sulfur conversion difficult. As a result, most reported discharge capacities remain below

80% of the theoretical limit. Second, polysulfide anions, formed as reaction intermediates, dissolve in the organic electrolyte and can migrate to the Li anode, where they reduce to Li_2S. This passivates the anode, depletes active material, and increases impedance. Additionally, repeated dissolution and precipitation alter cathode morphology, inducing strain and reducing cycle life (Liang et al., 2019).

Recently, Li//S batteries require higher sulfur loading and improved rate capability, exacerbating Li-metal anode issues. During charge/discharge cycles, Li dendrites grow rapidly with increasing current density, posing safety risks. Higher sulfur loading also generates more polysulfide ions, which react with Li chemically and electrochemically, causing low coulombic efficiency, capacity fading, and uneven Li deposition. Significant efforts focus on stabilizing Li-metal anodes, including artificial protection films, electrolyte reformulation, and current collector modifications. While progress has been made, the commercialization of Li//S batteries with Li-metal anodes remains challenging (Agostini et al., 2015). Given these challenges, Afghan authorities could facilitate investment in this field-first, by leveraging the country's abundant lithium resources in a technically and professionally efficient manner, and second, by exporting value-added products such as Li-ion batteries to the global market. This could create job opportunities for Afghan researchers, professionals, and youth, playing a crucial role in the sustainability of Afghanistan's economy.

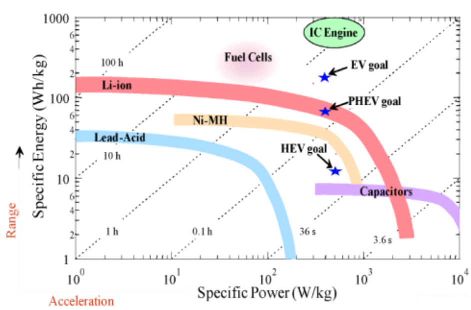

Figure 5. (a) various electrochemical energy storage and conversion devices.

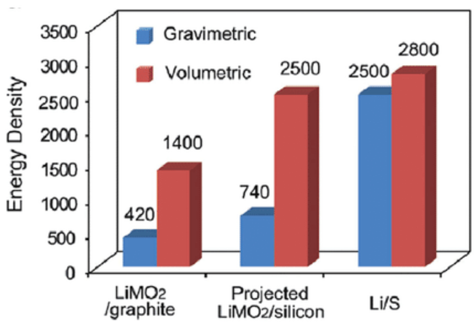

Figure 5. (b) theoretical energy density of three rechargeable battery systems.

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2.5 Nuclear Energy & Fusion: Enhancing reactor materials and coolant systems for safer and more efficient energy generation.

Economic development is a key indicator of a country's progress, reflecting improvements in living standards, production organization, and product quality. Two main approaches define economic development: income-based, measured by per capita income, and human-based, focused on human development. Initially assessed through economic factors like income and industrialization, development now includes indicators such as education and health. The relationship between human development (H&D) and economic growth (EGRW) has gained attention, with H&D viewed as expanding choices for healthier, longer lives (UN, 2018). The widely used H&D Index by UNDP measures development based on living standards, longevity, and access to information. The relationship between energy consumption (ENC) and economic development can be analyzed through two key variables: H&D and EGRW, both representing economic progress. Energy is vital for countries economic and social welfare, serving as a key production input. The industrial revolution and oil crises of 1973 and 1979 highlighted the significance of energy. Energy closely tied to production, growth of economy, and human development, energy is essential for sustainability. Both renewable and nonrenewable sources impact human welfare.

Here, we would like to focus on nonrenewable energy, and the nuclear energy is also considered a nonrenewable energy source. However, nuclear energy has positive and negative impacts on H&D. for instance, the potential for nuclear accidents, such as the disasters at Chernobyl and Fukushima, which have caused widespread damage and long-term health effects, and another is the nuclear fusion reactor (NFR). A nuclear fusion reactor (NFR) plant is a facility that generates electricity by harnessing the energy of nuclear fusion, the same process that fuels the sun and stars (Petrescu et al., 2016). Unlike traditional nuclear power plants that rely on nuclear fission (splitting heavy atoms), nuclear fusion plants aim to merge light atomic nuclei (usually isotopes of hydrogen) to release large amounts of energy. Many countries are producing a huge amount of nuclear energy, through the nuclear fusion reactions or plants around the world. The nuclear energy helps us to produce electricity by using it in a power plant, which is very beneficial in industrialization sector (Brook et al., 2014).

Based on the PB statical review in 2021, the USA and Europe have the highest generation and consumption of the nuclear energy, besides USA has the large number of nuclear power plants, therefore, USA is the major plyer of the globe in terms of nuclear energy market (Figure 6). Energy is crucial for human welfare and is directly interconnected with social, economic, and environmental sustainability-key pillars of sustainable development. According to the world energy council (WEC), energy is a fundamental driver of long-term economic growth (Aydin & Aydin, 2024). Therefore, investing in nuclear fusion research is essential to harness Afghanistan's abundant uranium and plutonium resources, advancing self-sufficiency and energy independence.

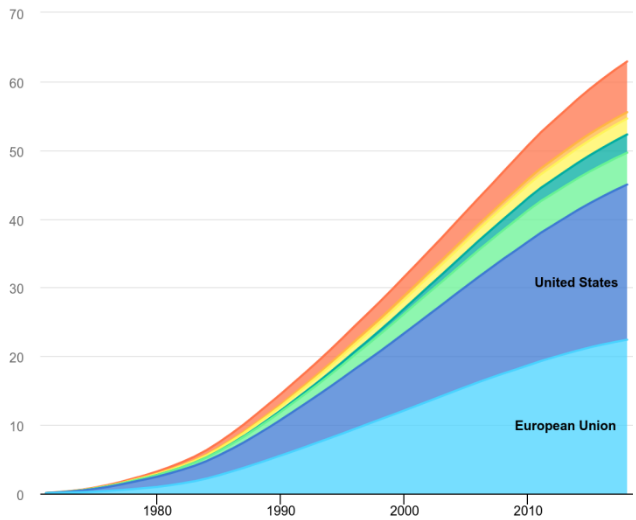

Figure 6. CumulativeCO_2 emissions avoided by global nuclear power in selected countries 1971-2018. Source: International Energy Agency.

3. CONCLUSION

In summary, achieving sustainable development in Afghanistan requires a multidimensional approach that integrates community-driven solutions with advanced technological innovations. This study highlights the pivotal roles of home economics and chemical engineering in addressing the country’s unique challenges. Home economics promotes sustainable lifestyles by emphasizing effective resource management, while chemical engineering provides technological solutions to mitigate environmental degradation, optimize energy production, and enhance industrial processes. Key areas of focus include the hydrogen economy, carbon capture, utilization and storage (CCUS), biofuels, green chemistry, batteries, energy storage, nuclear energy, and nuclear fusion. The increasing emphasis on CCUS is essential for Afghanistan's efforts to decarbonize its energy and industrial sectors, contributing to global climate change mitigation. Additionally, process intensification (PI) and the integration of renewable energy sources including hydrogen, wind, nuclear, geothermal, and solar are critical for improving energy efficiency and reducing dependence on fossil fuels.

These interdisciplinary efforts provide Afghanistan with a pathway to address environmental challenges while fostering economic growth and industrial development. Ultimately, fostering collaboration between home economics and chemical engineering can lead to sustainable solutions tailored to Afghanistan's socioeconomic and environmental context. This integrated approach not only meets immediate development needs but also ensures long-term sustainability, driving job creation, innovation, and national prosperity.

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