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Navigating the Future of Chemistry: Priorities and Opportunities for Sustainable Innovation (review)

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Abstract. The essay explores the shifting landscape of energy and chemical production, focusing on the growing emphasis on sustainability over the last decade. It highlights key research areas that have gained substantial attention, such as biorefineries, solar energy conversion, energy storage materials, and carbon dioxide utilization. The authors stress the need for innovative solutions in catalysis, process design, and the use of alternative raw materials and energy sources. They advocate for a more comprehensive view of sustainability, considering both economic and socio-environmental factors, and encourage a forward-looking approach to address future trends and challenges. This analysis aims to motivate researchers and industry players to pursue new technologies and methods that will drive a more sustainable future in the fields of chemistry and energy.

Keywords: Sustainability, Biorefinery, Solar energy conversion, Energy storage, Carbon dioxide utilization, Catalysis, Circular economy, Renewable resources.

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Introduction

The global energy and chemical production landscape is experiencing a significant shift, driven by the urgent need for sustainability and the potential of emerging technologies. As we confront the challenges of climate change, resource depletion, and environmental harm, the chemical industry finds itself at a pivotal moment. The shift from fossil fuel-based processes to more sustainable practices is not just a passing trend but a crucial necessity for the future of our planet [1]. This essay explores the priorities and opportunities presented by this transition, focusing on sustainability and the key advancements made in the past decade [2].

Traditionally, the chemical industry has been fundamental to economic growth, supplying vital materials and energy across sectors. However, conventional production methods have come with considerable environmental costs, including greenhouse gas emissions and ecological damage. The need for a fundamental shift is emphasized by growing societal demand for sustainable solutions and the realization that current practices are unsustainable. Moving forward, a comprehensive approach is essential, integrating sustainability into all aspects of chemical production—from sourcing raw materials to final applications [3,4].

Global greenhouse gas emissions have reached record levels, increasing by 1.3% in 2020, exacerbating the climate crisis (Figure 1).

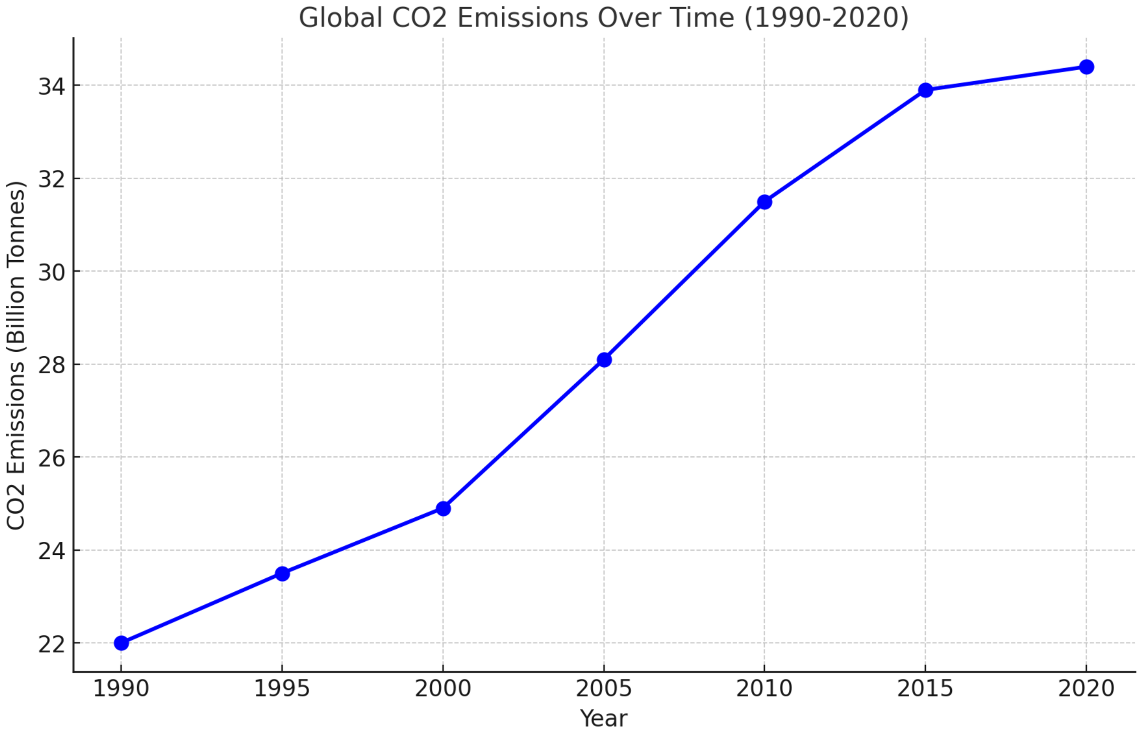

Figure 1. Solar reforming as an emerging technology for circular chemical industries

Scarcity of natural resources such as fossil fuels is exacerbated by growing demand, while the extraction and processing of raw materials is becoming increasingly costly and environmentally hazardous [5–7]. Social demand for environmentally friendly products is also increasing: according to surveys, more than 70% of global consumers prefer sustainably produced goods. At the same time, governments are tightening regulations to reduce emissions and implement environmentally friendly technologies, which requires companies to find new, cleaner and more efficient production methods, such as recycling waste and raw materials using pyrolysis [8,9].

One of the most promising strategies for promoting sustainability in the chemical industry is the use of renewable resources. Biomass, for example, provides a renewable alternative to fossil fuels, allowing the production of chemicals and fuels through biorefinery methods [5]. This not only lessens dependence on limited resources but also supports carbon neutrality by absorbing CO_2 from the atmosphere. Advances in lignin conversion technologies and the development of platform molecules are driving more efficient and sustainable biomass utilization [10]. The potential for biomass to serve as a key feedstock in the chemical industry is immense, and continued research is essential to fully realize its benefits.

Alongside biomass, solar energy presents another major opportunity for sustainable chemical production. Progress in materials for solar energy conversion, such as photocatalysts and solar cells, has accelerated in recent years [11]. These technologies allow sunlight to be directly converted into chemical energy, providing a clean and renewable power source. Cutting-edge research in artificial photosynthesis and water splitting is focused on replicating natural processes to sustainably produce fuels and chemicals [12]. By incorporating solar energy into chemical production, we can decrease reliance on fossil fuels and reduce the environmental impact of conventional methods [13].

Energy storage is a crucial element in the transition to a sustainable chemical industry. As renewable energy sources become more widespread, the demand for efficient storage solutions grows [14]. Advances in battery technologies, fuel cells, and supercapacitors are key to enabling the broad adoption of renewable energy. In this study, we conducted a thorough analysis of these technologies, employing specific criteria such as efficiency, capacity, and sustainability to evaluate their effectiveness. We selected relevant research based on their contributions to these criteria, ensuring a robust overview of current advancements in the field [15].

Materials and methods

The development of new materials and technologies for energy storage will be central to the future of sustainable chemistry. Additionally, utilizing carbon dioxide as a raw material offers a unique solution to both energy production and greenhouse gas reduction [16]. CO_2 utilization technologies seek to transform waste CO_2 into valuable chemicals and fuels, effectively closing the carbon loop. This approach not only helps combat climate change by lowering atmospheric CO_2 levels but also creates new avenues for chemical production. Rapid advancements in catalytic processes are making it possible to convert CO_2 into a variety of products, from fuels to polymers. We employed standardized criteria to evaluate the effectiveness of these catalytic processes, allowing us to compare their performance with existing methods. Integrating CO_2 utilization into the chemical industry marks a significant step toward achieving a circular economy [17].

While advancements in biomass utilization, solar energy conversion, energy storage, and CO_2 utilization are encouraging, sustainability extends beyond technological innovation. A holistic approach to sustainable chemistry must also address economic and socio-environmental considerations [18]. The shift to a sustainable chemical industry requires cooperation among researchers, industry leaders, and policymakers to create a supportive environment for innovation. This includes establishing favorable regulatory frameworks, fostering public-private partnerships, and investing in education and training to prepare the workforce for future challenges.

Additionally, the role of catalysis in advancing sustainability is of critical importance. Catalysis is a key technology that improves the efficiency and selectivity of chemical processes.

In our review, we provide a detailed comparison of new catalysts, both homogeneous and heterogeneous, highlighting how their innovations surpass existing technologies [19]. This discussion illustrates the ways in which new catalysts contribute to more sustainable practices by enabling reactions to occur under less extreme conditions, thus lowering energy consumption and reducing waste production. Therefore, continued research in catalysis is vital to fully realizing the potential of sustainable chemistry [20].

The future of chemistry is closely tied to the pursuit of sustainability. The shift from conventional fossil fuel-based methods to innovative, sustainable practices presents both challenges and opportunities [21]. By adopting renewable resources, utilizing solar energy, enhancing energy storage systems, and converting CO_2 into useful products, the chemical industry can play a key role in addressing global energy and environmental issues. However, achieving true sustainability requires a comprehensive approach that combines technological advancements with economic and socio-environmental considerations.

Reflecting on the progress made over the past decade, moving forward will demand ongoing investment in research, collaboration, and a steadfast commitment to fostering a sustainable future for both the chemical industry and the broader world. The aim of this study is to analyze the current state of research and assess the prospects of state-of-the-art technologies and practices that promote sustainability in the fields of chemistry and energy. The authors emphasize the significance of innovative solutions in areas such as bioprocessing, solar energy conversion, energy storage, and carbon dioxide utilization, while advocating for a comprehensive approach to sustainability that considers economic, social, and environmental aspects.

Results and discussion

The sustainable future of chemicals and energy is a critical area of focus as the world grapples with the dual challenges of climate change and resource scarcity. The chemical industry is responsible for approximately 10% of global greenhouse gas emissions, contributing significantly to climate change. In 2021 alone, the sector emitted over 1.2 billion tons of CO_2 in the U.S. [17]. This transformation is not only essential for environmental preservation but also presents a wealth of opportunities for innovation, economic growth, and societal well-being.

At the heart of a sustainable future for chemicals and energy lies the concept of a circular economy. Unlike the traditional linear model of production and consumption, which often leads to waste and environmental degradation, a circular economy emphasizes the continual use of resources. This model encourages the design of products and processes that minimize waste, promote recycling, and facilitate the reuse of materials. For instance, plastic waste is projected to triple by 2040 if current trends continue, highlighting the urgent need for innovative waste management strategies. In the chemical industry, this means developing processes that not only reduce the consumption of raw materials but also enable the recovery and repurposing of by-products [22,23]. The integration of waste-to-chemical processes can convert industrial waste into valuable feedstocks, thus closing the loop and reducing reliance on virgin materials. For example, companies like LanzaTech have successfully transformed industrial emissions into ethanol, demonstrating the viability of this approach [24].

Another promising avenue for achieving a sustainable future in the chemical sector is the utilization of renewable feedstocks. Biomass, for example, offers a renewable alternative to fossil fuels, allowing for the production of chemicals and fuels through biorefinery processes. It is estimated that biomass could meet up to 30% of global energy needs by 2030 [25]. Advances in biotechnology and enzymatic processes are enabling the efficient conversion of biomass into platform chemicals, which can serve as building blocks for a wide range of products. For instance, companies like Novozymes are developing enzymes that can convert agricultural residues into bio-based chemicals. By shifting towards renewable feedstocks, the chemical industry can significantly reduce its carbon footprint and contribute to a more sustainable energy landscape.

In addition to these industrial efforts, numerous scientists and researchers are making significant contributions to this field. Notable figures include Professor Sir Richard Friend from the University of Cambridge, who has conducted groundbreaking research on organic photovoltaics, aiming to improve solar energy efficiency for chemical processes [26]. His work is crucial in enhancing the sustainability of energy sources used in chemical synthesis.

Another key researcher is Dr. Jennifer A. Doudna, a pioneer in CRISPR technology, who is exploring its applications in bioengineering to optimize microorganisms for biofuel production [27]. Her innovative approach could lead to more efficient conversion processes, thereby supporting the chemical industry's shift toward renewable resources.

By shifting towards renewable feedstocks and embracing innovative practices, the chemical industry can significantly reduce its carbon footprint and contribute to a more sustainable energy landscape. These collaborative efforts among scientists, researchers, and industry leaders underscore the critical importance of interdisciplinary approaches in tackling the challenges of sustainability [28].

The urgency of this transition is further underscored by growing regulatory pressures and consumer demand for eco-friendly products. Recent studies show that 75% of consumers are willing to pay more for sustainable products, pushing companies to adopt greener practices. Additionally, international regulations, such as the European Green Deal, set ambitious targets for reducing emissions and promoting sustainable industry practices, necessitating a rapid shift in how chemicals are produced and used [29].

Statistics also reveal the economic imperative for sustainable practices. The global market for green chemicals is projected to reach $1 trillion by 2027, growing at a CAGR of over 10%. This shift not only highlights the increasing consumer preference for sustainable products but also signals a significant economic opportunity for companies that invest in sustainable technologies and practices. Furthermore, transitioning to a circular economy could save the global economy approximately $4.5 trillion by 2030 through improved resource efficiency and reduced waste, demonstrating that sustainability is not only an environmental imperative but also a pathway to economic resilience and growth [6].

These factors collectively highlight the critical need for a sustainable transformation in the chemical industry, making it essential to invest in innovative technologies and frameworks that support this transition.

In addition to biomass, the utilization of carbon dioxide (CO_2) as a raw material presents a unique opportunity for sustainable chemical production. CO_2 utilization technologies aim to convert waste CO_2 into valuable chemicals and fuels, effectively addressing both energy production and greenhouse gas emissions. This approach not only helps mitigate climate change by reducing atmospheric CO_2 levels but also creates new pathways for chemical production [30,31]. Research in this field is rapidly advancing, with promising developments in catalytic processes that enable the conversion of CO_2 into a range of products, from fuels to polymers. The integration of CO_2 utilization into the chemical industry represents a significant step towards achieving a circular economy and reducing the environmental impact of chemical production [32].

The role of renewable energy sources in the sustainable future of chemicals cannot be overstated. The transition from fossil fuels to renewable energy sources, such as solar, wind, and hydropower, is essential for reducing the carbon intensity of chemical production. The development of materials for solar energy conversion, such as photocatalysts and solar cells, has gained momentum in recent years. These technologies enable the direct conversion of sunlight into chemical energy, offering a clean and renewable source of power [33–35]. Innovations in artificial photosynthesis and water splitting are at the forefront of this research, aiming to mimic natural processes to produce fuels and chemicals sustainably. By integrating renewable energy into chemical production, we can significantly reduce our dependence on fossil fuels and mitigate the environmental impact of traditional processes [36].

Energy storage is another critical component of the sustainable future of chemicals and energy. As renewable energy sources become more prevalent, the need for efficient energy storage solutions is paramount. Advances in battery technology, fuel cells, and supercapacitors are essential for enabling the widespread adoption of renewable energy. Research in this area focuses on improving the efficiency, capacity, and sustainability of energy storage systems, ensuring that energy generated from renewable sources can be effectively utilized when needed. The development of new materials and technologies for energy storage will play a pivotal role in the future of sustainable chemistry [37].

Moreover, the importance of catalysis in promoting sustainability cannot be overstated. Catalysis serves as a key enabling technology that enhances the efficiency and selectivity of chemical processes. The development of new catalysts, both homogeneous and heterogeneous, is crucial for driving the transition to more sustainable practices [11,38,39]. Catalysts can facilitate reactions under milder conditions, reduce energy consumption, and minimize waste generation. As such, ongoing research in catalysis is essential for unlocking the full potential of sustainable chemistry.

Collaboration among stakeholders is vital for realizing a sustainable future in chemicals and energy. This includes partnerships between academia, industry, and government to foster innovation and create supportive regulatory frameworks. Policymakers play a crucial role in establishing incentives for sustainable practices, such as tax breaks for companies that invest in renewable technologies or grants for research in sustainable chemistry [40]. Additionally, public-private partnerships can facilitate the sharing of knowledge and resources, accelerating the development and implementation of sustainable technologies.

Education and training are also essential components of a sustainable future. As the chemical industry evolves, the workforce must be equipped with the skills and knowledge necessary to navigate this transition. Educational institutions should prioritize sustainability in their curricula, fostering a new generation of scientists and engineers who are well-versed in sustainable practices and technologies. Furthermore, ongoing professional development opportunities for current industry professionals will ensure that the workforce remains adaptable and capable of meeting the challenges of a rapidly changing landscape [3].

Outlining a sustainable future for chemicals and energy requires a multifaceted approach that encompasses innovative technologies, collaborative efforts, and a commitment to circular economy principles. By embracing renewable feedstocks, utilizing CO_2 as a raw material, integrating renewable energy sources, and advancing energy storage solutions, the chemical industry can significantly reduce its environmental impact and contribute to a more sustainable energy landscape [41]. The role of catalysis, collaboration among stakeholders, and education will be pivotal in driving this transition. As we move forward, it is essential to recognize that the path to sustainability is not only a necessity but also an opportunity for innovation, economic growth, and a healthier planet for future generations [42].

In recent years, significant achievements have been made in the field of sustainable development within the chemical industry and energy sector, reflecting a growing awareness of the need to transition to more environmentally friendly practices. One major advancement is the development of new biotechnologies that enable the efficient conversion of agricultural waste and other renewable resources into valuable chemicals. Companies like LanzaTech and Novozymes have pioneered processes that utilize microorganisms to transform carbon dioxide and biomass into useful products, including biofuels and biochemical [24,43].

Additionally, there has been an increase in the number of chemical companies implementing recycling technologies. For instance, BASF and Dow are actively working on processes that convert plastic waste into new raw materials, contributing to a circular economy and reducing the need for virgin resources. The development of bioplastics and biodegradable materials, such as polylactic acid (PLA), represents another important step in minimizing environmental impact, with these materials being utilized in packaging and various industries to provide more sustainable solutions [29]. The implementation of advanced technologies and processes, such as catalytic reactors and energy-efficient systems, has allowed many chemical plants to significantly reduce energy consumption and lower greenhouse gas emissions. Companies like SABIC and Shell have adopted carbon capture and storage (CCS) solutions, which substantially decrease their carbon footprint. Many organizations are also beginning to develop circular economy strategies where waste is converted into new products. For example, Unilever has announced plans to make all its packaging materials recyclable or reusable by 2025, demonstrating a strong commitment to sustainability.

These achievements highlight that the chemical industry is moving toward a more sustainable future by actively embracing innovation and adapting to the evolving demands of the market and society.

Solar-Driven Chemistry

As the world grapples with the pressing challenges of climate change and resource depletion, the need for innovative solutions in energy production and chemical synthesis has never been more urgent. Solar-driven chemistry emerges as a transformative approach that harnesses the abundant energy of the sun to drive chemical reactions, offering a pathway toward sustainable practices in the chemical industry. This paradigm shift not only aims to reduce reliance on fossil fuels. It also seeks to minimize greenhouse gas emissions and promote the use of renewable resources [44]. In this exploration of solar-driven chemistry, we will delve into its principles, applications, and the potential it holds for a sustainable future. At its core, solar-driven chemistry leverages solar energy to facilitate chemical transformations. This approach is inspired by natural processes, particularly photosynthesis, where plants convert sunlight, water, and carbon dioxide into glucose and oxygen. By mimicking these processes, researchers aim to develop systems that can convert solar energy into chemical energy, effectively storing it for later use. The fundamental mechanisms involved in solar-driven chemistry include photochemical reactions, photocatalysis, and artificial photosynthesis, each playing a crucial role in the development of sustainable chemical processes [40,45].

Solar-driven chemistry can play a pivotal role in energy storage. As renewable energy sources, such as solar and wind, become more prevalent, the need for efficient energy storage solutions is paramount. Solar-driven chemical processes can convert excess solar energy into chemical fuels, effectively storing energy for later use. This approach not only addresses the intermittency of renewable energy sources but also provides a means to decarbonize sectors that are challenging to electrify, such as heavy industry and transportation [46]. For example, solar-driven processes can produce hydrogen or hydrocarbons that can be stored and utilized as fuels, providing a versatile solution for energy storage and transportation. The work of researchers like Dr. Jennifer A. Doudna also highlights the potential of CRISPR technology in optimizing biological pathways for fuel production, further enhancing the efficiency and sustainability of these processes [27].

Notable researchers in this field include Professor Michael Grätzel from École Polytechnique Fédérale de Lausanne, known for his pioneering work on dye-sensitized solar cells [47]. His research has significantly advanced the efficiency of solar energy capture, laying the groundwork for its application in artificial photosynthesis. Another key figure is Dr. Nathan

S. Lewis from Caltech, who focuses on developing photoelectrochemical systems for solar fuel production [48]. His innovative approaches to integrating catalysts and light-absorbing materials have made strides in improving the efficiency of solar-driven chemical reactions.

In summary, while existing chemical synthesis and energy production methods largely rely on fossil fuels and high-energy inputs, solar-driven chemistry - particularly through photocatalysis and artificial photosynthesis - presents a substantial leap forward. By utilizing renewable solar energy and promoting CO_2 conversion, these technologies represent a significant advancement in our quest for sustainable practices in the chemical industry, aligning more closely with global sustainability goals.

The integration of solar-driven chemistry into the chemical industry holds significant potential for reducing carbon emissions and promoting sustainability. Traditional chemical processes often rely on fossil fuels as both energy sources and feedstocks, contributing to environmental degradation. By shifting to solar-driven methods, the industry can reduce its carbon footprint and transition toward a more sustainable model. For instance, solar-driven processes can be employed in the production of essential chemicals, such as ammonia, which is traditionally produced through energy-intensive Haber-Bosch processes. Researchers are exploring alternative pathways that could significantly lower energy consumption and emissions associated with ammonia production by utilizing solar energy.

Photocatalysis is one of the most promising areas within solar-driven chemistry. It involves the use of light-activated catalysts to accelerate chemical reactions. Photocatalysts can harness sunlight to drive reactions that would otherwise require significant energy input. For instance, titanium dioxide (TiO_2) is a widely studied photocatalyst that can facilitate the degradation of pollutants in water and air when exposed to UV light [49]. More advanced photocatalysts are being developed to enable the conversion of CO_2 into valuable chemicals, such as methanol or hydrocarbons, effectively addressing both energy production and greenhouse gas emissions [50] (Figure 2). This dual functionality positions photocatalysis as a key player in the transition to a low-carbon economy [33].

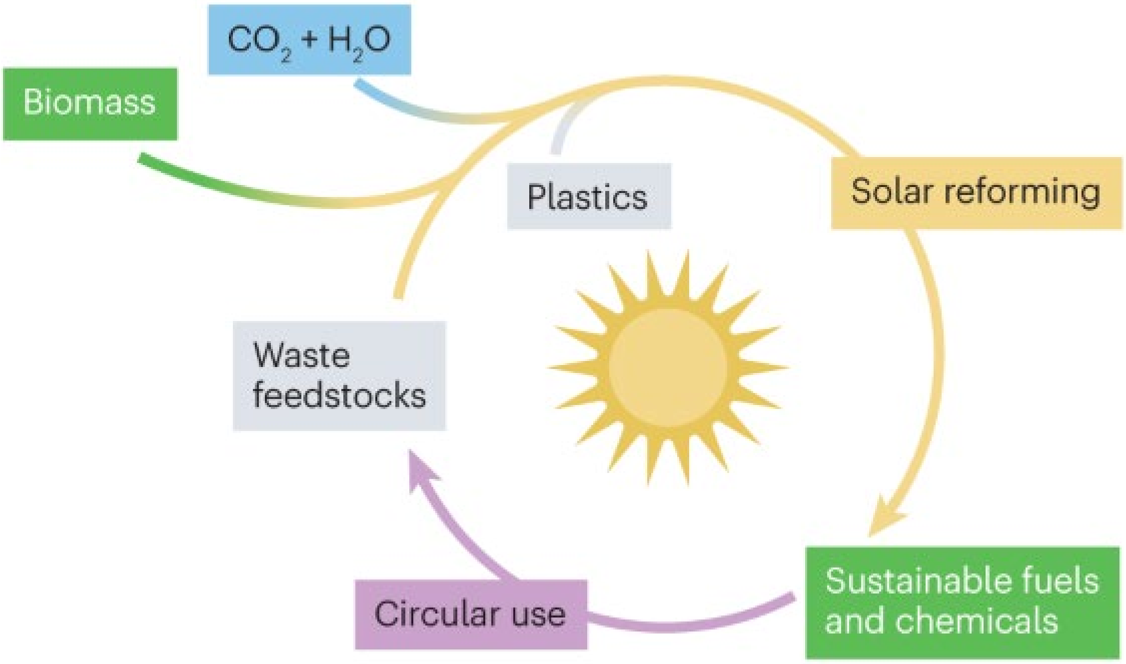

Figure 2. Solar reforming as an emerging technology for circular chemical industries

Artificial photosynthesis represents another exciting frontier in solar-driven chemistry. Researchers are working to create systems that mimic the natural process of photosynthesis, aiming to produce fuels and chemicals directly from sunlight, water, and CO_2. These systems typically consist of light-absorbing materials, catalysts, and reaction chambers designed to optimize the conversion of solar energy into chemical energy. For example, recent advancements in the development of photoelectrochemical cells have shown promise in efficiently converting solar energy into hydrogen fuel through the splitting of water molecules [51]. This hydrogen can then be utilized as a clean energy carrier or as a feedstock for various chemical processes [52].

Artificial Photosynthesis further distinguishes itself from prior methods by directly mimicking the natural process of photosynthesis, which has evolved over millions of years to efficiently harness solar energy [53]. Unlike earlier synthetic methods, which typically involve complex, energy-intensive processes, artificial photosynthesis aims to achieve similar efficiencies with minimal environmental impact. This innovative approach not only enhances energy capture but also integrates carbon sequestration into the chemical synthesis process, promoting sustainability in a way that traditional techniques cannot match [3].

In summary, while existing chemical synthesis and energy production methods are largely reliant on fossil fuels and high-energy inputs, solar-driven chemistry, particularly through photocatalysis and artificial photosynthesis, presents a substantial leap forward. By utilizing renewable solar energy and promoting CO_2 conversion, these technologies represent a significant advancement in our quest for sustainable practices in the chemical industry, aligning more closely with global sustainability goals [16].

The integration of solar-driven chemistry into the chemical industry holds significant potential for reducing carbon emissions and promoting sustainability. Traditional chemical processes often rely on fossil fuels as both energy sources and feedstocks, contributing to environmental degradation. By shifting to solar-driven methods, the industry can reduce its carbon footprint and transition toward a more sustainable model. For instance, solar-driven processes can be employed in the production of essential chemicals, such as ammonia, which is traditionally produced through energy-intensive Haber-Bosch processes. By utilizing solar energy, researchers are exploring alternative pathways that could significantly lower energy consumption and emissions associated with ammonia production. Moreover, solar-driven chemistry can play a pivotal role in energy storage. As renewable energy sources, such as solar and wind, become more prevalent, the need for efficient energy storage solutions is paramount. Solar-driven chemical processes can convert excess solar energy into chemical fuels, effectively storing energy for later use. This approach not only addresses the intermittency of renewable energy sources but also provides a means to decarbonize sectors that are challenging to electrify, such as heavy industry and transportation. For example, solar-driven processes can produce hydrogen or hydrocarbons that can be stored and utilized as fuels, providing a versatile solution for energy storage and transportation [40].

The development of solar-driven chemistry is not without its challenges. One of the primary hurdles is the efficiency of solar energy conversion. While significant progress has been made in recent years, many solar-driven processes still face limitations in terms of efficiency and scalability. Researchers are actively working to improve the performance of photocatalysts and artificial photosynthesis systems, exploring new materials and reaction conditions to enhance energy conversion rates. Additionally, the integration of solar-driven processes into existing industrial frameworks requires careful consideration of economic viability and infrastructure development [54].

Collaboration among academia, industry, and government is essential for advancing solar-driven chemistry. Public-private partnerships can facilitate the sharing of knowledge, resources, and funding, accelerating the development and commercialization of solar-driven technologies. Furthermore, supportive policies and incentives can encourage investment in research and development, fostering innovation in this field. As the global community increasingly recognizes the importance of sustainability, the potential for solar-driven chemistry to contribute to a low-carbon future is gaining traction. Education and outreach also play a crucial role in promoting solar-driven chemistry [55]. Raising awareness about the benefits and potential applications of solar-driven processes can inspire the next generation of scientists and engineers to pursue careers in this field. Educational institutions should prioritize sustainability in their curricula, equipping students with the knowledge and skills needed to tackle the challenges of the future. Additionally, public engagement initiatives can help foster a broader understanding of the importance of solar-driven chemistry in addressing climate change and promoting sustainable practices [56].

Solar-driven chemistry represents a promising avenue for achieving a sustainable future in energy production and chemical synthesis. By harnessing the power of the sun, this innovative approach has the potential to revolutionize the chemical industry, reducing reliance on fossil fuels and minimizing environmental impact [57]. Through advancements in photocatalysis, artificial photosynthesis, and energy storage, solar-driven chemistry can contribute to a low-carbon economy while addressing the pressing challenges of climate change [58]. As research and development in this field continue to progress, collaboration among stakeholders and a commitment to education will be essential for realizing the full potential of solar-driven chemistry. Embracing this transformative approach is not only a necessity for sustainability but also an opportunity for innovation and economic growth in the years to come [29].

A major plus point of photosynthesis is its role in absorbing carbon dioxide, which helps reduce the concentration of this greenhouse gas in the atmosphere. This makes photosynthesis an important process in the fight against climate change. However, photosynthesis also has its disadvantages [59,60]. Natural photosynthetic systems have a low solar energy conversion efficiency of about 1-2%. This limits their potential application as a direct source of energy for technological needs.

Photocatalysis, on the other hand, is an artificial process that uses light to accelerate a chemical reaction using a photocatalyst. This process is being actively studied for applications such as water purification, separation of water into hydrogen and oxygen, and carbon dioxide utilization. One of the main advantages of photocatalysis is that it can be used to create hydrogen, a clean and renewable fuel. Also, photocatalysis can be used for environmentally friendly processes such as the degradation of pollutants in air and water [56,61,62]. However, photocatalysis also has its limitations. Current photocatalysis technologies often require expensive materials such as titanium or platinum-containing catalysts, which limits their widespread application. In addition, the efficiency of photocatalysis under real-world conditions is sometimes low because strong solar illumination or even ultraviolet radiation is required, limiting its use in sunlight-deficient regions.

If we compare photosynthesis and photocatalysis with other energy conversion technologies, such as solar cells (photovoltaic panels), the latter have a much higher solar energy conversion efficiency of about 15-20% [63,64]. However, solar panels require significant capital investment and cannot directly participate in carbon dioxide conversion or biomolecule synthesis processes, making them less versatile than photocatalysis or photosynthesis [65,66].

Thus, photosynthesis and photocatalysis have their unique advantages related to their environmental friendliness and potential to reduce carbon dioxide concentrations. Nevertheless, their limited efficiency and high material costs make them less attractive compared to conventional energy generation technologies. Nevertheless, active research in these areas is ongoing, which could lead to significant increases in their efficiency and cost reductions in the future.

Impact of Catalysis

Catalysis plays a pivotal role in the transition toward sustainable chemistry and energy production, serving as a key enabler for the development of efficient, low-carbon processes. As the world shifts its focus to renewable energy sources and sustainable practices, the importance of catalysis becomes increasingly pronounced. Catalysts are substances that accelerate chemical reactions without being consumed in the process, allowing for more efficient transformations of raw materials into valuable products. This efficiency is crucial in minimizing energy consumption and reducing waste, thereby addressing the environmental challenges posed by traditional chemical processes [67].

In the context of solar-driven chemistry, catalysis is essential for harnessing solar energy to drive chemical reactions. Photocatalysts, for instance, utilize sunlight to facilitate reactions that convert CO_2 into useful chemicals or fuels, effectively addressing both energy production and greenhouse gas emissions. The development of advanced photocatalysts that can operate under visible light and exhibit high selectivity is a significant area of research, with the potential to revolutionize how we produce chemicals sustainably. Moreover, catalysis is integral to the concept of circular economy, where the focus is on minimizing waste and maximizing resource efficiency. Catalytic processes can enable the recycling of materials, such as converting waste plastics back into usable chemicals or fuels. This not only reduces the environmental impact of waste but also conserves valuable resources, aligning with the principles of sustainability.

The integration of catalysis into renewable energy systems, such as hydrogen production through water splitting, further exemplifies its impact. Catalysts that facilitate the efficient conversion of solar energy into hydrogen fuel can help decarbonize sectors that are challenging to electrify, such as heavy industry and transportation. This shift not only promotes energy security but also contributes to a significant reduction in carbon emissions [54]. In summary, catalysis is a cornerstone of the new sustainable chemistry landscape. Its ability to enhance reaction efficiency, enable the use of renewable resources, and facilitate waste recycling positions it as a critical technology in the quest for a low-carbon future. As research continues to advance in this field, the potential for catalysis to drive innovation and competitiveness in the chemical industry remains immense, paving the way for a more sustainable and environmentally friendly approach to chemical production.

Molecular catalysis represents a transformative approach in the field of chemistry, offering unique opportunities to enhance reaction efficiency and selectivity at the molecular level. Unlike traditional heterogeneous catalysts, molecular catalysts are defined by their precise structures, allowing for tailored interactions with substrates. This specificity enables the acceleration of chemical reactions while minimizing the formation of unwanted by-products, which is crucial for sustainable industrial processes.

One of the most significant advantages of molecular catalysis is its ability to facilitate complex multistep reactions. By employing well-defined molecular catalysts, chemists can streamline synthetic pathways, reducing the need for multiple reaction steps and thereby improving overall efficiency. This capability is particularly valuable in the production of fine chemicals and pharmaceuticals, where high selectivity and yield are paramount [68].

Recent advancements in molecular catalysis have also opened new avenues for addressing environmental challenges. For instance, the development of catalysts that can efficiently convert CO_2 into valuable chemicals not only helps mitigate greenhouse gas emissions but also contributes to the circular economy by recycling waste into useful products.

Additionally, molecular catalysts can be designed to operate under mild conditions, further reducing energy consumption and enhancing sustainability.

Prominent researchers in this field include Professor Frances H. Arnold, who was awarded the Nobel Prize in Chemistry for her pioneering work on the directed evolution of enzymes, a subset of molecular catalysts [69]. Her research has led to the development of more efficient catalysts that can facilitate complex reactions with high selectivity. Another notable figure is Dr. David W.C. MacMillan, whose work on organocatalysis has transformed the field by demonstrating how small organic molecules can serve as powerful catalysts [70]. His innovations have enabled more sustainable reaction conditions and have applications in pharmaceutical synthesis, where minimizing waste is crucial. Furthermore, Dr. Carolyn R. Bertozzi has made significant contributions by designing molecular catalysts that can selectively functionalize biomolecules [71]. Her research not only advances synthetic chemistry but also has implications for biomedicine, allowing for the development of targeted therapies with improved efficacy. These scientists and their research exemplify the transformative potential of molecular catalysis in both synthetic efficiency and environmental sustainability, illustrating how innovative approaches can lead to practical solutions in addressing global challenges.

Moreover, the integration of molecular catalysis with emerging technologies, such as artificial intelligence and machine learning, is paving the way for the discovery of novel catalysts with unprecedented performance. By leveraging computational methods, researchers can predict catalyst behavior and optimize reaction conditions, accelerating the development of new catalytic systems. Molecular catalysis holds immense potential for revolutionizing chemical processes. Its ability to enhance efficiency, selectivity, and sustainability positions it as a key player in the future of green chemistry. As research continues to evolve, the possibilities for molecular catalysis to drive innovation and address global challenges are boundless, making it an exciting frontier in the quest for sustainable solutions.

New Materials for Energy

The development of new materials is crucial for advancing energy technologies and achieving a sustainable future. As the world increasingly turns to renewable energy sources, the need for innovative materials that can enhance energy conversion, storage, and efficiency becomes paramount. These materials play a vital role in various applications, including solar energy, batteries, fuel cells, and thermoelectric devices [72].

One of the most promising areas of research is in the field of solar energy conversion. Advanced materials, such as perovskite solar cells and quantum-dot solar cells, have shown remarkable efficiency improvements and cost-effectiveness compared to traditional silicon-based solar cells. Additionally, the development of photoelectrochemical cells that utilize novel catalysts can facilitate the conversion of sunlight into chemical fuels, such as hydrogen, thereby providing a clean energy source [73].

In the realm of energy storage, new materials are essential for improving the performance of batteries and supercapacitors. For instance, the exploration of nanostructured materials, such as graphene and transition metal oxides, has led to significant advancements in lithium-ion batteries, enhancing their capacity, charge/discharge rates, and overall lifespan. Furthermore, the development of solid-state batteries, which utilize solid electrolytes instead of liquid ones, promises to increase safety and energy density, making them a viable option for electric vehicles and portable electronics [74].

Fuel cells, which convert chemical energy directly into electricity, also benefit from the innovation of new materials. The design of advanced catalysts, particularly those that can operate efficiently at lower temperatures, is critical for enhancing the performance and reducing the costs of fuel cells. Research into alternative materials, such as non-precious metal catalysts, aims to make fuel cell technology more accessible and economically viable [75,76].

Thermoelectric materials, which can convert waste heat into electricity, are another area of focus. The development of high-performance thermoelectric materials can improve energy efficiency in various applications, from industrial processes to automotive systems. The exploration and development of new materials for energy applications are vital for addressing the global energy challenge. By enhancing energy conversion, storage, and efficiency, these materials not only contribute to the advancement of renewable energy technologies but also play a crucial role in the transition toward a sustainable, low-carbon future. As research continues to progress, the potential for innovative materials to revolutionize the energy landscape remains significant.

Conclusion

The pursuit of new materials for energy applications is a cornerstone of the transition to a sustainable and low-carbon future. As the world grapples with the challenges of climate change and the depletion of fossil fuels, innovative materials are essential for enhancing the efficiency and effectiveness of renewable energy technologies. From advanced solar cells and high-performance batteries to efficient fuel cells and thermoelectric materials, the development of these new materials holds the promise of transforming how we generate, store, and utilize energy.

The integration of cutting-edge research in materials science with emerging technologies, such as nanotechnology and artificial intelligence, further amplifies the potential for breakthroughs in energy applications. By tailoring materials at the molecular and nanoscale, scientists can create systems that not only improve energy conversion and storage but also reduce environmental impact and promote sustainability. As we move forward, continued investment in research and development, along with collaboration across disciplines, will be crucial in unlocking the full potential of new materials. The innovations that arise from this endeavor will not only drive technological advancements but also contribute to a more sustainable and resilient energy landscape. Ultimately, the future of energy lies in our ability to harness the power of new materials, paving the way for a cleaner, more efficient, and sustainable world.

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The contribution of the authors

Ozan Kartal conducted the entire study independently, including the design, execution, and analysis of the research. His sole effort in this project ensured its successful completion and the development of the manuscript.

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Химия болашағын бағдарлау: тұрақты инновацияның басымдықтары мен мүмкіндіктері (шолу)

Аңдатпа: Бұл шолу мақаласында соңғы бірнеше онжылдықта никель гидроксиді бойынша жүргізілген зерттеулерге шолу жасалады, бұл физикада да, химияда да маңызды инженерлік қолданбалы, әсіресе батареяларда маңызды материал. Ол екі белгілі полиморфтардың, α-Ni(OH)2 және β-Ni(OH)2 құрылымдарын сипаттаудан басталады. Мақалада сонымен қатар никель гидроксидінде жиі кездесетін гидратация, қабаттасу ақаулары, механикалық кернеулер және иондық қоспалардың қосылуы сияқты әртүрлі бұзылулар зерттеледі. Байланысты материалдар, соның ішінде интеркалирленген α-туындылары мен негізгі никель тұздары да талқыланады. Шолу никель гидроксидін синтездеудің химиялық және электрохимиялық тұндыру, золь-гель синтезі, химиялық қартаю, гидротермиялық және солвотермиялық синтез, электрохимиялық тотығу, микротолқын көмегімен синтездеу және сонохимиялық әдістер сияқты бірнеше әдістерін жинақтайды. Соңында никель гидроксидінің белгілі физикалық қасиеттері — магниттік, дірілдік, оптикалық, электрлік және механикалық

— зерттеледі. Қорытынды бөлім осы материалдардың әлеуетті құнды қасиеттерінің қысқаша мазмұнын және никель гидроксиді негізіндегі белгісіз үлгілерді анықтау және сипаттау әдістерін ұсынады.

Түйін сөздер: Тұрақтылық, Биоөңдеу зауыты, Күн энергиясын түрлендіру, Энергияны сақтау, Көмірқышқыл газын пайдалану, Катализ, Циркулярлық экономика, Жаңартылатын ресурстар.

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Навигация в будущее химии: приоритеты и возможности для устойчивых инноваций (обзор)

Аннотация: В эссе исследуется меняющийся ландшафт энергетического и химического производства, с упором на растущее внимание к устойчивости за последнее десятилетие. В нем освещаются ключевые области исследований, которые привлекли значительное внимание, такие как биопереработка, преобразование солнечной энергии, материалы для хранения энергии и использование углекислого газа. Авторы подчеркивают необходимость инновационных решений в катализе, проектировании процессов и использовании альтернативного сырья и источников энергии. Они выступают за более комплексный взгляд на устойчивость, учитывая как экономические, так и социально-экологические факторы, и поощряют дальновидный подход к решению будущих тенденций и проблем. Цель этого анализа — мотивировать исследователей и участников отрасли на изучение новых технологий и методов, которые приведут к более устойчивому будущему в области химии и энергетики.

Ключевые слова: Устойчивое развитие, Биопереработка, Преобразование солнечной энергии, Хранение энергии, Утилизация углекислого газа, Катализ, Круговая экономика, Возобновляемые ресурсы.

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