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Research Development
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KINGDOM OF SAUDI ARABIA

Emerging Innovative Technologies in Sustainable Environment and Essential Needs

The Research, Development and Innovation Authority (RDIA)

December 2024

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INTRODUCTION

Research, Development, and Innovation (RDI) play a vital role in advancing environmental sustainability and meeting essential human needs. By fostering sustainable practices, RDI enables breakthroughs in energy efficiency, waste reduction, and resource conservation, helping mitigate environmental impact. Innovations in fields like renewable energy, water purification, and sustainable agriculture address crucial challenges like climate change, pollution, and food security. RDI not only drives eco-friendly solutions but also promotes economic growth, creating green jobs and resilient systems. Ultimately, RDI is essential for building a sustainable future where human needs are met in harmony with preserving the environment for future generations.

Technology foresight is a strategic process used to anticipate and prepare for future technological developments and their potential impacts. By systematically analyzing trends, emerging technologies, and socio-economic shifts, foresight enables organizations and policymakers to make informed decisions, guide innovation, and shape policy. It goes beyond mere prediction, fostering resilience and adaptability in an ever-evolving landscape. Through methods like scenario planning, Delphi studies, and horizon scanning, technology foresight identifies opportunities and challenges, ensuring readiness for diverse futures. This proactive approach is essential for navigating uncertainties and driving sustainable progress in fields as diverse as sustainability of environment and essential needs.

The report Emerging Innovative Technologies in Sustainable Environment and Supply of Essential Needs explores ten groundbreaking advancements addressing critical environmental challenges and ensuring the supply of essential resources. As the world faces unprecedented demands due to rapid urbanization, climate change, and resource scarcity, innovation is key to developing sustainable solutions.

This report highlights technologies across diverse fields, each contributing to a more resilient and sustainable future. An example to that is application of elastocalorics technologies in heating and cooling which offer an efficient an eco-friendly alternative to conventional methods

Advanced water purification with hydrogels and nanobubble technology tackles water scarcity by enhancing filtration and recycling processes. AI-driven agriculture and biotechnology promote sustainable farming practices, improving yield while reducing environmental impact. Reflective materials help cool urban areas, mitigating the heat island effect, while AI-based tools monitor water quality and guide resource-efficient farming.

Further, this report highlights the role of artificial intelligence in advancing materials for carbon capture, supporting climate change mitigation efforts, and facilitating climate monitoring for proactive environmental protection. Novel catalysts are also being developed to reduce pollution, preserving natural ecosystems. Together, these technologies represent a proactive approach to safeguarding our environment while ensuring the supply of essential needs for future generations.

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METHODOLOGY

The technical foresight methodology at the National Research, Development and Innovation Observatory (NRDIO) consists of four main axes: monitoring, analysis, evaluation, and alignment which are explained as follows:

1. Monitoring

When forecasting emerging technologies, the National Research, Development and Innovation Observatory (NRDIO) incorporates **Proactive and Reactive Monitoring** to enhance the accuracy and responsiveness of analysis.

A) Proactive Monitoring

Proactive monitoring involves anticipating trends, innovations, and breakthroughs before they gain mainstream attention. This helps in identifying emerging technologies early on, allowing for strategic preparation and planning.

- **Horizon scanning:** NRDIO regularly reviews scientific literature, patent filings, venture capital funding reports, technology roadmaps, and expert opinions. Tools like artificial intelligence and text mining are utilized to identify trends from large datasets.

- **Delphi method:** A panel of experts was established to gain foresight into potential technological advances. This iterative consultation helps forecast new developments.

- **Trend analysis:** NRDIO examines historical data on similar technologies to predict growth curves and tipping points. This includes analyzing adjacent technologies and potential convergences.

- **Technology readiness level (TRL)**: The development stage of technologies is continuously evaluated based on their TRL, helping to understand when they might mature into scalable solutions.

B) Reactive Monitoring

Reactive monitoring focuses on responding to real- world developments as they happen. It involves tracking the real-time progress of technologies that have already been identified as emerging, and adjusting forecasts based on new data. It is performed by the following methods:

- Continuous real-time data collection: Systems are implemented to track real-time developments such as new product launches, regulatory changes, mergers and acquisitions, and shifts in the competitive landscape.

- Signal detection: Key indicators are monitored (e.g., breakthroughs, government policy shifts, industry adoption rates) that suggest when a technology is gaining momentum or encountering barriers.

- Social media and news analysis: Sentiment analysis and media monitoring tools are used to capture public and industry reactions to technological developments.

- Post-launch evaluation: Once an emerging technology reaches the market, its performance is evaluated through user feedback, financial performance metrics, and industry reviews.

- Utilizing the above methods, the next steps follow:

- Strategic adjustment and reflection: Based on the real-time insights gathered through reactive monitoring, NRDIO continuously adjusts its strategic forecasts, and priorities to ensures that NRDIO remains adaptable, making course corrections where necessary to capitalize on opportunities or mitigate risks.

- Interdisciplinary stakeholder engagement: Engaging Interdisciplinary experts from the industry and academia to gain a holistic view and qualitative feedback that complements quantitative data.

2. Analysis

The analysis activity in the technical foresight methodology followed at NRDIO consists of the following elements:

- Technical analysis: This includes providing an overview of the field under which the tech signal falls to place it in a broader context. The technical analysis also includes providing an overview of the tech signal in terms of describing it, explaining its principles and advantages, and its points of superiority over competing and alternative technologies.

- Economic analysis: This includes estimating the size of the global market, the size of the local market, the factors driving the technology market, the most prominent companies involved, their market values, and analyzing the effects of emerging technology on other technologies; as new markets full of economic opportunities may be created, but they may negatively affect other markets to the point of excluding them from competition, which is usually caused by disruptive technologies.

- Risk analysis: The risks and challenges associated with emerging technologies are analyzed, whether ethical, legal, environmental, social, or otherwise. This also includes suggesting how to address potential obstacles, which leads to improving the chances of success of the emerging technology and achieving its desired goals.

3. Evaluation

Technological signals are evaluated quantitatively and qualitatively by a scientific committee of experts specialized in various fields, through several main criteria that aim to measure the extent of their impact and feasibility from different aspects, as follows:

1. Strategic Impact: This criterion shows the role of technology in solving global challenges, and evaluates the importance of technology in dealing with the major challenges facing the world, such as climate change, food security, natural resources, and others.

2. Long-term impact: This criterion measures the sustainability of the impact of technology in the long term in different sectors, and determines the extent of the technology's ability to bring about permanent change or a long-term impact on individuals, companies, or industries.

3. Need within the sector: This criterion determines the extent to which a technology is considered in demand within the technology sector itself or within related industries. The need for technology is determined based on current gaps in the sector, whether in manufacturing, services, or other technical systems.

4. Consumers' attitude towards technology: This criterion measures the extent to which consumers or end users are interested in the new technology, whether at the individual or corporate level.

5. Economic impact and commercial benefit: This criterion assesses the expected economic benefit of the technology, including commercial profits and market growth, the potential market size, and the value of commercial returns.

6. Technology Readiness Level (TRL): This criterion determines the extent to which the technology has progressed in its development cycle, from research and development to commercialization. The closer the technology is to commercial readiness, the more important it is in terms of investment and adoption.

In order to achieve a broader, more diverse, and more accurate perspective on emerging technologies and their various impacts. A score of (05-) is given to each of the six aforementioned aspects; 5 indicates the 'highest' importance, while 0 indicates the 'lowest' importance. The "Evaluation" activity involves also the engagement of stakeholders (such as academics, companies, regulators, and other parties related to research, development, and innovation) through a questionnaire dedicated to technology foresight.

4. Alignment

The results of technology foresight are aligned to strategic plans and implementation steps that can be taken at the policy or investment level, where the results of monitoring, analysis and evaluation are translated into practical recommendations that can be implemented at the policy and regulatory level or the strategic plans of institutions. The aim is to ensure that technology foresight does not remain within the scope of theory or research only, but is transformed into concrete steps to stimulate innovation and support the knowledge-based economy.

The technology signals highlighted in this report are linked to the goals of Saudi Vision 2030 and aligned with the following National RDI Missions in Sustainability of Essential Needs:

1. Plant 10 billion trees across KSA by 2040.

2. Protect 30% of the Kingdom›s land and sea by 2035.

3. Develop technologies in food for sustainable and resilient food systems to achieve more than 50% self-sufficiency by 2040.

4. Achieve net-zero emissions by 2060.

5. Decrease the withdrawal of non-renewable water by 90% and the cost of water production by 50% by 2035.

6. Reduce summer surface temperatures by 4°C by 2040.

7. Develop and adopt innovative cooling technologies to reduce cooling electricity consumption by 30% by 2040.

In the following pages, this report will present selected emerging innovative technologies in Sustainability of Essential Needs, as follows:

1. Advanced Water Purification with Hydrogels

2. Water Treatment and Recycling with Nanobubble and Electro-Ceramic   Technologies

3. Smart Monitoring of Water Quality

4. Sustainable AI-based Agriculture

5. Agricultural Biotechnology

6. Advanced Carbon Capture Materials

7. Developing Catalysts for Environmental Protection

8. Elastocalorics for Cooling and Heating Applications

9. Cooling Cities with Supercooling Materials

10. AI-Enhanced Climate Change Monitoring

This report provides a brief overview of each of these fields, followed by a review of some of the tech signals/advancements that fall under them, with an economic overview of the current and future global market size estimate for these technologies, and an assessment of their importance through several quantitative and qualitative criteria, according to the perspective of the experts of the Scientific Committee of the National Research, Development and Innovation Observatory
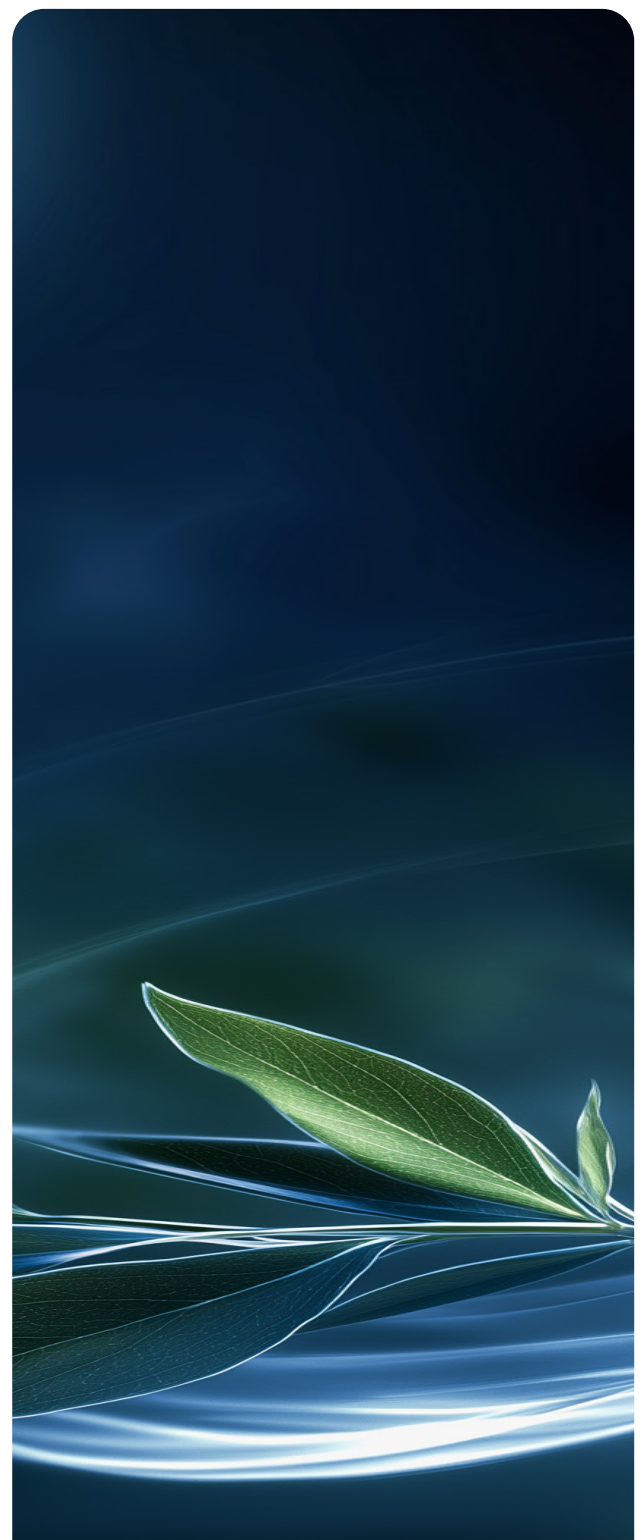
01

Advanced Water Purification with Hydrogels

Zwitterionic hydrogels are an innovative class of materials characterized by their incorporation of both positive and negative ionic charges within the same molecular structure, referred to as zwitterions. These hydrogels exhibit an exceptional affinity for water, making them highly hydrophilic. This unique property allows them to effectively attract and bind a wide array of micropollutants, including those that are often challenging to eliminate using conventional water treatment methods. The hydrogels possess a highly porous structure and a large surface area, enabling them to quickly absorb and retain significant amounts of contaminants. As a result, zwitterionic hydrogels have emerged as a promising tool for purifying water, especially in contexts where rapid and efficient removal of pollutants is crucial.

The effectiveness of zwitterionic hydrogels is largely attributed to their unique molecular configuration. These hydrogels are composed of a network of polymer chains that expand when exposed to water, forming a matrix that captures and immobilizes micropollutants. The zwitterionic groups within the hydrogel structure facilitate interactions with pollutants through various mechanisms, including electrostatic attractions, hydrogen bonding, and other intermolecular forces. This multifaceted approach enables the hydrogels to effectively target a broad range of contaminants, such as organic molecules, heavy metals, and microplastics, making them versatile tools for water purification.

The development of zwitterionic hydrogels marks a significant advancement in the field of water purification, offering a promising solution to the growing global concerns over water scarcity and pollution. As the need for effective and affordable water treatment solutions intensifies, these hydrogels present an innovative approach to tackling the challenge of micropollutants, which are increasingly recognized as substantial threats to both public health and the environment.

Beyond their role in water treatment, zwitterionic hydrogels have the potential for applications in a variety of fields, including medical devices, sensors, and bioseparation technologies. Their unique properties make them particularly effective in capturing and eliminating a diverse range of biological and chemical substances, potentially leading to new innovations in healthcare, environmental monitoring, and various industrial processes.

For more information, click here

Tech Signal

Using Zwitterionic Hydrogels to swiftly remove micropollutants from water

In a new paper in Nature Water, a recent breakthrough by researchers at MIT has led to the development of a method that utilizes zwitterionic hydrogels to rapidly and effectively remove micropollutants from water. This new technique represents a significant leap forward in water purification technology, specifically addressing the challenge of eliminating harmful substances such as pesticides, pharmaceuticals, and other chemical pollutants that contaminate water supplies. Even in very low concentrations, these contaminants pose serious risks to human health and aquatic ecosystems. The newly developed zwitterionic hydrogels offer a highly effective and scalable solution to this problem, making them a promising tool for widespread water purification efforts.

The research team demonstrated that these hydrogels could remove over 99% of various micropollutants from water samples within a matter of minutes. This rapid rate of adsorption significantly outperforms traditional methods, such as activated carbon filters or reverse osmosis, which are often slower and less efficient at capturing certain contaminants.

One of the key advantages of zwitterionic hydrogels is their versatility. Unlike traditional water treatment methods that may require multiple steps or different types of filters to effectively remove a wide range of contaminants, zwitterionic hydrogels can target a broad spectrum of pollutants in a single step. Moreover, these hydrogels do not depend on high pressure or chemical additives, making them more energy-efficient and environmentally friendly. Additionally, zwitterionic hydrogels can be regenerated and reused multiple times without a significant decline in performance, thereby reducing both the costs and the waste associated with water purification.

Their scalability is another notable benefit, making them suitable for a variety of applications, ranging from municipal water treatment plants to portable water filters for household use or in disaster relief situations. The MIT researchers suggest that these hydrogels could be integrated into existing filtration systems or employed as standalone devices, offering a flexible and adaptable solution to water contamination challenges worldwide.

The development of zwitterionic hydrogels by the MIT team represents a significant advance in water purification technology. By providing a rapid, efficient, and versatile method for removing micropollutants from water, these hydrogels hold the potential to improve access to clean water for millions of people globally. As further research is conducted and the technology continues to evolve, zwitterionic hydrogels could become a crucial tool in the global effort to maintain safe and sustainable water resources for future generations.

For more information, click here

Economic Overview

The significant expansion in hydrogels market underscores the increasing demand for hydrogels across various industries, such as healthcare, agriculture, and cosmetics. The growth is likely driven by advancements in hydrogel applications, particularly in wound care, drug delivery, and water retention systems, reflecting their versatility and importance in emerging technologies and sustainable solutions.

The global hydrogels market (Billion USD)
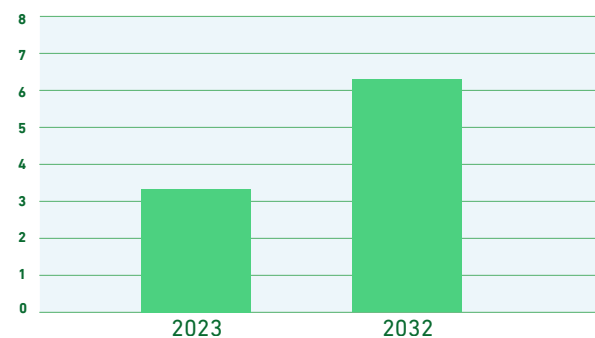
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Ensuring Environmental Sustainability", specifically by:

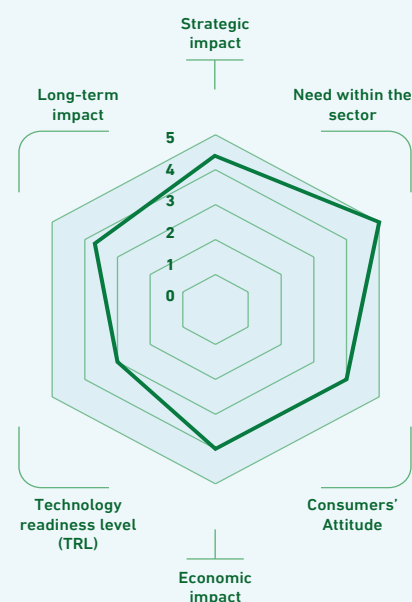▪ Rationalizing and using treated and renewable water.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

▪ Decrease the withdrawal of non-renewable water by 90% and the cost of water production by 50% by 2035.

For more information, click here

Multi-Dimensional Evaluation

Advanced Water Purification with Hydrogels

02

Water Treatment and Recycling with Nanobubbl and Electro-Ceramic Technologies

Wastewater presents a significant environmental and health risk, producing greenhouse gases (GHGs) emissions nearly equal to those from the aviation industry. However, with appropriate policies, it could become a valuable resource, generating energy for 500 million people , supplying over 10 times the amount of water provided by current desalination efforts, and reducing global fertilizer use by over 10%.

An analysis by the World Energy Outlook (WEO) reveals that the water sector, including wastewater collection and treatment, consumes 4% of global electricity, with wastewater treatment accounting for about a quarter of this energy use. The sector also contributes approximately 3% of total global GHGs emissions. However, there are significant opportunities to utilize energy embedded in wastewater, offering potential for more sustainable practices.

Currently, only 11% of domestic and industrial wastewater is reused, largely due to the presence of contaminants like heavy metals and toxic chemicals that require complex treatments.

Nanobubble technology enhances wastewater treatment by improving gas transfer efficiency, which can facilitate processes such as oxidation, disinfection, and contaminant removal. The extremely small size of nanobubbles allows them to remain stable in water for extended periods, increasing their interaction with contaminants and enabling more effective breakdown or removal. While the process can indirectly improve energy efficiency due to its effectiveness, the core focus here is on improving contaminant removal in wastewater recycling.

Nanobubble technology involves the generation of ultra-small gas bubbles, typically less than 100 nanometers in diameter. These bubbles enhance gas transfer efficiency in water, allowing for better oxygenation and improving processes such as wastewater treatment, agriculture, and aquaculture. Nanobubbles can stay suspended in water longer due to their small size and stability, making them effective in reducing chemical use, enhancing irrigation efficiency, and boosting water purification. This innovative technology also offers potential environmental benefits by improving resource efficiency and supporting sustainable industrial practices by treating and recycling wastewater.

On the other hand, electro-ceramic desalination technology uses ceramic membranes to separate salts and impurities from water through an electrochemical process. This approach is highly effective in treating challenging industrial wastewater, particularly in harsh conditions like acidic or oxidizing environments. The ceramic membranes are durable, cost-efficient, and energy-saving, enabling the recovery of up to 98% of water for reuse. This technology reduces reliance on traditional, more energy-intensive desalination met˜hods and offers a sustainable solution for industries looking to recycle water and minimize environmental impact.

For more information, click here

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Tech Signal

Revolutionizing Water Sustainability with Nanobubble Technology and Electro-Ceramic Desalination

Kran, a startup based in Puerto Varas, Chile, has gained international recognition for its innovative nanobubble technology. The company recently won the Siemens Water Innovation Challenge at the ACADES 2024 Congress. Kran aims to combine cutting-edge technology with environmental responsibility. The company›s rapid growth has seen it expand from Patagonia to Silicon Valley, being named one of the "Top Innovators" by the World Economic Forum.

Kran's nanobubble solutions are tailored for various sectors such as agriculture, aquaculture, and industrial processes, enhancing water efficiency and reducing the need for chemicals and energy. Their technology promotes significant environmental benefits, including saving in water consumption, improved industrial productivity, and lower carbon footprints.

The company is driven by three core principles: being at the forefront of science, offering high-tech solutions, and maintaining a 100% green approach. Kran continues to innovate with the goal of improving water reuse, regenerating polluted environments, and minimizing harmful chemical use.

Nanobubbles offer significant benefits, including improving irrigation efficiency, which can lead to water savings of over 50%. They also enhance washing processes in food factories by reducing both water and chemical use, and enable energy savings in wastewater treatment, allowing industrial water to be reused for irrigation. Kran aims to further boost agricultural productivity, decrease reliance on drinking water for industrial processes, restore polluted environments, and lower the use of environmentally harmful chemicals through its innovative nanobubble technology.

On the other side, Membrion, the company based in Seattle, developed a patented electro-ceramic desalination technology that eliminates the need for expensive treatments like boiling or chemical processing and avoids off-site disposal. The system is capable of recovering up to 98% of water, allowing for effective recycling even in tough conditions. This innovation significantly reduces costs and supports sustainable water management in industrial settings.

Membrion specializes in advanced electro-ceramic desalination technology, which is designed to treat harsh industrial wastewater. Their patented system focuses on removing problematic ions, improving water reuse, and reducing chemical, labor, and energy costs. Membrion's technology is particularly effective for treating acidic and oxidizing wastewater streams, helping industries such as aquaculture, agriculture, and mining enhance water efficiency while meeting sustainability goals. Their solutions also support businesses in expanding wastewater treatment capacities and achieving compliance with environmental regulations.

For more information, click here

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Economic Overview

The figure highlights the growing significance of the water recycle and reuse market, which is projected to experience substantial growth from 2022 to 2032. This trend underscores the increasing global focus on sustainable water management to address challenges like water scarcity, population growth, and industrial expansion.

The water recycle and reuse market (Billion USD)
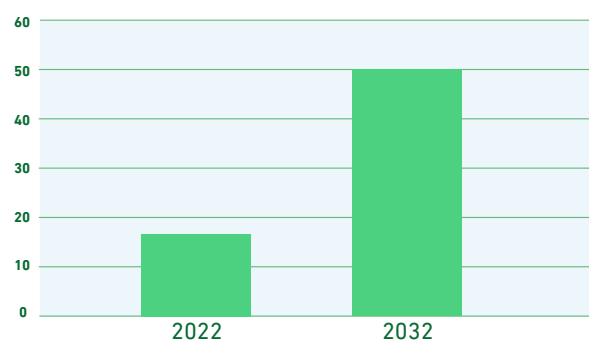
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Ensuring Environmental Sustainability", specifically by:

- Rationalizing and using treated and renewable water
- Reducing various types of pollution..

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

- Decrease the withdrawal of non-renewable water by 90% and the cost of water production by 50% by 2035.

For more information, click here

Multi-Dimensional Evaluation

Water Treatment and Recycling with Nanobubble Technology

03

Smart Monitoring of Water Quality

Urban water pollution has become one of the most pressing environmental challenges in cities worldwide. Rapid urbanization, industrialization, and inadequate infrastructure contribute to the release of untreated sewage, toxic chemicals, and waste into water bodies, threatening human health and ecosystems. To address this growing problem and enhance global water resilience, Artificial Intelligence (AI) and robotics offer innovative solutions that can revolutionize water management practices.

AI plays a pivotal role in monitoring and analyzing urban water systems at a systems level. By integrating machine learning algorithms and advanced data analytics with centralized data platforms, AI can process vast amounts of data collected not only from in-situ sensors placed in rivers, lakes, and wastewater facilities but also from remote sensing technologies, historical databases, and predictive models. These systems aggregate and analyze results at a broader scale, offering a holistic understanding of urban water dynamics.

One key application is the ability to detect pollutants and track pollution sources. Moreover, AI systems excel in predicting potential contamination events by identifying patterns and anomalies in water quality data, such as spikes in chemical concentrations, changes in turbidity, or microbial activity. For example, machine learning algorithms can analyze sensor data combined with weather forecasts, industrial activity logs, and land use changes to forecast the likelihood of contamination due to stormwater runoff, industrial discharges, or agricultural effluents. This predictive capability empowers authorities to implement timely preventative measures, such as redirecting water flows, issuing public warnings, or deploying treatment solutions before contamination impacts public health.

Furthermore, AI-powered forecasting models assist city planners and utility operators in predicting water demand, assessing the impact of climate change on urban water resources, and optimizing water treatment processes. By analyzing data at the systems level, AI ensures that urban water systems remain resilient and sustainable, capable of adapting to both immediate challenges and long-term changes.

Robotics enhances these capabilities by providing practical tools for cleaning and maintaining water bodies. Autonomous robots equipped with sensors and cameras can monitor hard-to-reach areas, such as underground pipes and reservoirs, to detect leaks and blockages that may lead to contamination. Additionally, water-cleaning robots, such as aquatic drones, are being deployed to collect plastic waste and debris from rivers, lakes, and harbors. These machines can operate efficiently in areas that are too dangerous or inaccessible for human workers.

Together, AI and robotics enable a proactive, data-driven approach to combating urban water pollution. By integrating these technologies into urban water management systems, cities can reduce pollution, protect ecosystems, and ensure access to clean water. As climate change and population growth place increasing pressure on global water resources, leveraging AI and robotics will be essential to building resilient water systems that can adapt to future challenges.

For more information, click here

Tech Signal

Leveraging AI and Robotics to Combat Urban Water Pollution

Aging water infrastructure contributes significantly to urban pollution, driving the need for better pipeline rehabilitation and asset management solutions. AI-powered predictive analytics and intelligent fault detection are proving essential in helping utilities identify critical infrastructure issues, reduce wastewater discharge, and optimize treatment processes. As untreated wastewater flows downstream and is consumed by towns and villages, it can lead to widespread disease affecting both underprivileged and affluent communities.

To resolve that, Fluid Analytics Inc. (founded in 2022 in California) is tackling urban water pollution by utilizing robotics and artificial intelligence to monitor the health of water infrastructure, assess waterway conditions, and track the spread of waterborne diseases on a large scale. Through the application of proprietary machine learning models and advanced mathematical algorithms, trained on diverse global datasets, the company is effectively overseeing over 1.3 billion liters of urban water pollution while enabling the diversion, treatment, and reuse of 800 million liters daily.

The company›s groundbreaking work in global freshwater conservation earned it recognition as a leading innovator at the World Economic Forum's annual meeting in Davos, Switzerland. This honor, supported by UpLink, highlights Fluid Analytics› use of AI to mitigate risks associated with wastewater pipeline failures, offering crucial solutions for improving urban water resilience.

Committed to combating urban water pollution, Fluid Analytics has developed a state-of-the-art platform that monitors water infrastructure, assesses the condition of waterways, and tracks waterborne diseases. By leveraging proprietary datasets and unique machine learning models, the company has deployed technologies that monitor over 400 million gallons of urban wastewater spills and facilitate the treatment and reuse of 200 million gallons daily. The company currently monitors a population of more than 17.5 million people for potential waterborne diseases, which serve as indicators of sewage contamination.

The company's expertise spans a wide range of areas including environmental engineering, public health, water pollution, and AI-powered multi-sensor inspections.

A comparable company in the field of AI-driven water infrastructure monitoring is FIDO Tech, established in the United Kingdom. FIDO Tech specializes in AI-powered water leak detection, offering solutions that significantly reduce water loss and enhance pipeline management. Their technology utilizes advanced algorithms to analyze acoustic data, achieving a 92% accuracy rate in identifying leaks. This precision enables utilities to promptly address critical infrastructure issues, thereby minimizing wastewater discharge and optimizing treatment processes. FIDO Tech›s innovative approach has been adopted by various water utilities, contributing to improved urban water resilience and supporting global freshwater conservation efforts.

For more information, click here

|01| |02|

Economic Overview

Advancements in sensor technologies, AI-powered analytics, and real-time monitoring systems are driving the expansion in The water quality monitoring market, and reflecting a global commitment to ensuring sustainable and safe water supplies for residential, industrial, and agricultural needs.

The water quality monitoring market (Billion USD)
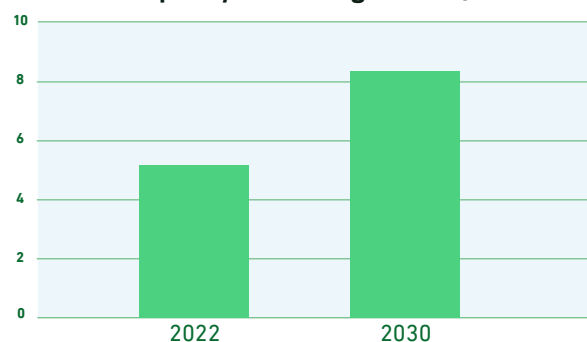
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Protecting the Country›s vital resources", specifically by:

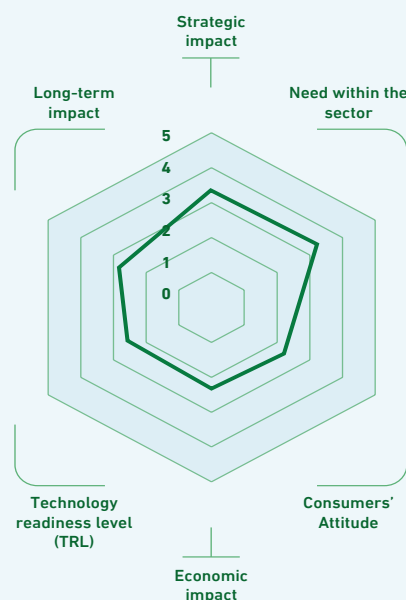▪Ensuring sustainable use of water resources.▪

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

▪ "Decrease the withdrawal of non-renewable water by 90% and the cost of water production by 50% by 2035".

For more information, click here

Multi-Dimensional Evaluation

Leveraging AI for Monitoring Water Quality

04

Sustainable AI-based Agriculture

Agriculture faces critical challenges related to climate change, water scarcity, environmental degradation, and reliance on conventional energy sources. Traditional practices often prioritize productivity and profitability over long-term sustainability, leading to biodiversity loss, soil degradation and health risks for humans and animals.

There is an increasing tendency to adopt "sustainable AI-based production agriculture» that exploits the integration of Artificial Intelligence (AI) in agriculture to address contemporary challenges and promote sustainable practices.

The integration of AI in agriculture supports sustainable practices by optimizing resource use, reducing environmental impact, and enhancing productivity. AI technologies contribute to ecosystem conservation, efficient resource management, and improved crop yields. AI can enhance agricultural productivity, sustainability, and precision through various applications:

1.Precision Agriculture: AI can optimize crop management by monitoring soil and crop health, detecting diseases, and managing water usage. AI-driven technologies like drones and sensors enable real-time data collection and analysis, improving decision-making and resource efficiency.

2.Automated Farming: AI-powered robots and drones can perform tasks such as weeding, harvesting, and spraying, reducing labor costs and increasing operational efficiency. These technologies help in precise application of inputs, minimizing wastage, and enhancing crop quality.

3.Energy Management: AI can facilitate the integration of renewable energy sources in agricultural operations, optimizing energy usage and reducing dependency on fossil fuels. Predictive analytics and smart energy planning can further improve energy efficiency in farming practices.

4.Livestock Monitoring: AI techniques, including sensors and cameras, enable real-time health monitoring of livestock, ensuring better animal welfare and productivity. AI systems can identify patterns and potential health issues early, allowing timely interventions.

5.Water Management: AI enhances precision water management by analyzing geospatial data, real-time sensor inputs, and weather forecasts to optimize irrigation practices. This leads to efficient water use, essential for regions with limited water resources.

AI holds significant promise for advancing sustainable agriculture by improving efficiency, productivity, and environmental stewardship. It is recommended to continue research and development to address the challenges and harness the full potential of AI in agriculture, ensuring food security and sustainability for future generations.

Tech Signal

Utilizing Advanced AI for Sustainable Production Agriculture

The advent of advanced artificial intelligence (edge AI) may herald a new era in sustainable agriculture. Researchers at the University of Liège have outlined a roadmap for integrating this technology into farming practices, aiming to enhance the efficiency, quality, and safety of agricultural production while tackling various environmental, social, and economic challenges.

Sustainable agriculture aims to efficiently feed a growing global population. Digital technologies, particularly AI, can significantly benefit agriculture by improving practices that boost efficiency, yield, quality, safety and sustainability (e.g. through increased carbon sequestration and protection). Edge AI involves implementing AI in a sophisticated computing environment. This technology allows calculations to be performed close to the data collection point, rather than in a centralized cloud or off-site datacenter. As a result, devices can make smarter decisions faster without needing to connect to remote cloud systems.

In a new study published in Nature Sustainability, the authors explored how to address these challenges and integrate AI into agricultural systems to meet the demands of sustainable food production. It's shown that deploying AI in agriculture presents challenges and requires innovative solutions and appropriate infrastructure. Despite the challenges, particularly in the face of climate change, the potential benefits are promising.

The University of Liège, among other institutes, played a pivotal role in this study, offering cutting-edge resources and expertise in AI and sustainable agriculture. University of Liège researchers have developed innovative edge AI solutions and conducted thorough analyses of their potential impact on farming practices.

These findings align with the growing trend of integrating advanced technologies into agriculture to achieve sustainability goals. The adoption of edge AI can revolutionize agricultural practices by enhancing resource efficiency, improving crop quality, and reducing environmental impacts. This technology is emerging as a vital component for the future of sustainable agriculture.

The applications are extensive: enhancing crop management with real-time data, optimizing the use of resources like water and fertilizers, reducing post-harvest losses, increasing food safety, and improving monitoring and response to changing weather conditions. This technological revolution, that could transform food production and consumption, paves the way for smarter, more environmentally-friendly agriculture.

For more information, click here

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Economic Overview

The growth in the use of AI in agriculture indicates the rising adoption of AI technologies in the agriculture sector, driven by advancements in precision farming, crop monitoring, predictive analytics, and automated machinery. The expansion highlights the growing emphasis on improving agricultural efficiency, sustainability, and productivity through innovative AI solutions.

The AI in Agriculture market (Billion USD)
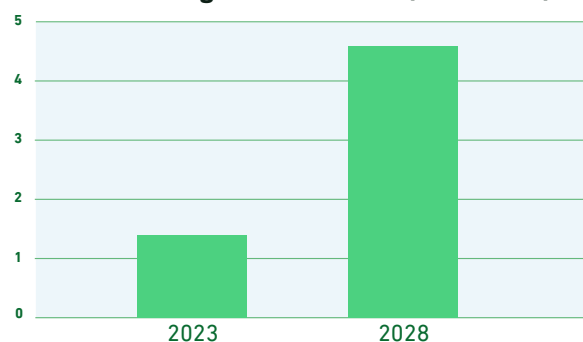
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Protecting the Country›s vital resources", specifically by:

- Ensuring development and food security.

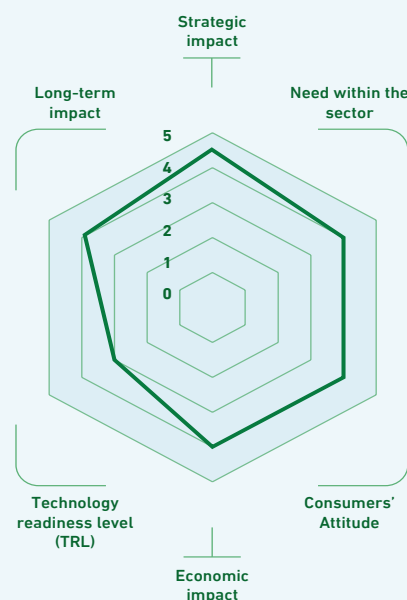## Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Plant 10 billion trees across KSA by 2040.

- Develop technologies in food for sustainable and resilient food systems to achieve more than 50% self-sufficiency by 2040.

For more information, click here

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Multi-Dimensional Evaluation

Sustainable AI-based Agriculture

05

Agricultural Biotechnology

Biotechnology has the potential to revolutionize food production by making it more cost-effective, efficient, and environmentally friendly. Biotechnology can help address global food supply challenges, such as population growth and climate change (which leads to desertification and, therefore, to lack of arable land), by developing genetically modified crops that are more resilient to weeds, pests, and harsh weather. Additionally, biotechnology innovations aim to reduce reliance on harmful chemical pesticides through the creation of biopesticides, which use natural materials like plants and minerals to protect crops safely. These advancements are crucial for providing nutritious food to current and future populations.

Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) genome editing is revolutionizing food production by enabling precise genetic modifications in crops, such as nutrient-enhanced tomatoes and disease-resistant wheat. These advances help address food security, improve crop yields, and reduce the need for pesticides. With engineered CRISPR tools, scientists can target specific genes to enhance desirable traits, such as nutritional content or resistance to climate stress. Future developments aim to improve editing precision and accessibility, allowing more rapid, sustainable agricultural innovations that meet global food demands and contribute to a healthier, resilient food system.

The article "How Helpful May Be a CRISPR/Cas-Based System for Food Traceability?" in MDPI foods explores the potential of CRISPR/Cas technology for enhancing food traceability and safety, emphasizing its application in genetically modifying plants for improved transparency in food supply chains. CRISPR›s precision allows for targeted genetic modifications, which are valuable for creating identifiable markers in food products, enabling reliable traceability from production to consumption. Beyond editing, CRISPR/Cas systems are also effective in detecting pathogens, allergens, and contaminants, making them instrumental in food quality monitoring. This dual functionality addresses both safety and authenticity concerns, as it supports tracing product origins and maintaining supply chain integrity.

The study suggests that the flexibility of CRISPR could significantly benefit regulatory frameworks, allowing more stringent verification of food sources and boosting consumer confidence in biotechnologically modified foods. Additionally, CRISPR's capabilities in gene expression analysis and environmental monitoring could be leveraged to prevent fraud and mislabeling in food industries. By combining CRISPR-based tools with existing traceability protocols, the food industry can enhance transparency, particularly in complex supply chains that often face challenges in tracking and verifying product sources.

For more information, click here

| 01 | | 02 | | 03 |

Tech Signal

Genetic Engineering and CRISPR-Crafted Food

Biotechnology is transforming the food industry, using genetic engineering to create cruelty-free and environmentally friendly products. Fungi, a diverse group of organisms, offer promising sources of nutritious and flavorful proteins, fats, antioxidants, and more.

Researchers at the Lawrence Berkeley National Laboratory are working on the use of genetic engineering to enhance the natural properties of fungi for innovative food production. The paper published in Nature Communications: «Edible mycelium bioengineered for enhanced nutritional value and sensory appeal using a modular synthetic biology toolkit» explores the potential of genetically modifying the edible fungus Aspergillus oryzae to improve its nutritional value and sensory qualities for food applications. Researchers developed a synthetic biology toolkit, including CRISPR-Cas9 methods, to enhance levels of ergothioneine (a potent antioxidant) and heme (for flavor and color). The engineered fungi could be easily processed into meat-like products, offering a sustainable alternative to traditional meat. This work also highlights the broader potential of bioengineering fungi for diverse food production applications.

This team has developed a CRISPR-Cas9 toolkit to modify the genome of Aspergillus oryzae, commonly known as koji mold. This fungus has been used for centuries in East Asian fermentation processes. The team focused on increasing the production of heme, which gives meat its color and flavor, and ergothioneine, an antioxidant with cardiovascular health benefits. These modifications turned the fungi red, allowing them to be processed into meat-like patties with minimal preparation.

The team aims to further enhance the fungi›s texture and lipid composition for a more meat-like experience. This work highlights the potential of fungi to serve as easy-to-grow protein sources, offering a sustainable alternative to traditional meat substitutes and cultured meat. The CRISPR-Cas9 toolkit represents a significant advancement in synthetic biology, facilitating the genetic engineering of multicellular fungi. In one project, the team worked to create a new dish using the fungus Neurospora intermedia. This fungus can convert leftovers into a protein-rich food, demonstrating the potential to bridge the gap between laboratory research and food innovation.

The genetic engineering of fungi for food production showcases the vast potential of these organisms to create new, sustainable foods. The CRISPR-Cas9 toolkit developed by the research team enables precise and efficient gene editing, paving the way for future advancements in the field of synthetic biology and biomanufacturing. This work not only offers new possibilities for food science but also integrates sophisticated culinary applications to create desirable and nutritious food products.

For more information, click here

|01| |02|

Economic Overview

The figure showcases the steady growth of the plant breeding and CRISPR plants market, which highlights the rising adoption of advanced genetic technologies, such as CRISPR, to enhance crop productivity, disease resistance, and climate resilience.

The plant breeding and CRISPR plants market (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Protecting the Country›s vital resources", specifically by:

▪Ensuring development and food security.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

▪Plant 10 billion trees across KSA by 2040.

▪Develop technologies in food for sustainable and resilient food systems to achieve more than 50% self-sufficiency by 2040.

For more information, click here

Multi-Dimensional Evaluation
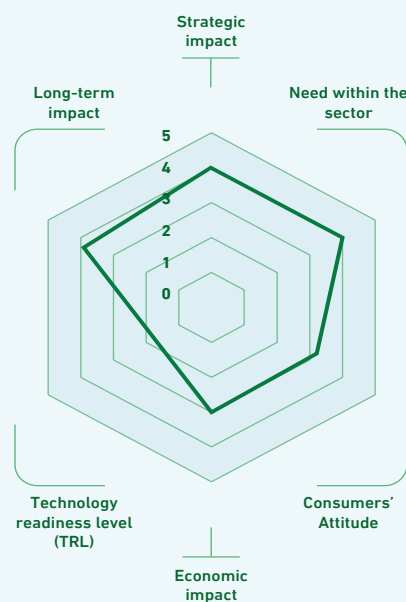
Agricultural Biotechnology

06

Advanced Carbon Capture Materials

Carbon Dioxide Removal (CDR) and Carbon Capture, Utilization, and Storage (CCUS) are critical technologies in the fight against climate change, offering potential pathways to reduce atmospheric CO_2 levels and mitigate industrial emissions. While CDR focuses on removing CO_2 directly from the air through natural and technological methods, CCUS aims to capture emissions at their source, preventing them from entering the atmosphere. These approaches complement emission reduction efforts and are increasingly recognized as essential components for achieving global temperature targets, despite facing challenges in scalability, cost, and societal acceptance.

With the urgency to develop scalable carbon-capture technologies growing alongside the rapid acceleration of climate change, the creation of new materials to remove atmospheric carbon is often a slow, repetitive process.

To expedite these discoveries, researchers are employing advanced artificial intelligence techniques, similar to those used in generating images from text prompts.

There is a challenge in finding the appropriate materials for capturing carbon, among thousands of possible solutions, like finding needles in a haystack, where trial and error are far too time-consuming. With a huge number of possibilities to sift through, identifying materials that effectively absorb carbon requires innovative methods such leveraging generative AI to address this challenge.

Artificial intelligence (AI) is transforming the search for materials optimized for carbon capture by accelerating the exploration of vast chemical spaces. Traditional experimental methods to design materials, such as metal-organic frameworks (MOFs), are limited by time, cost, and feasibility constraints. AI-driven generative models, however, can create and evaluate thousands of hypothetical materials, predicting their suitability based on CO_2 adsorption, stability, and scalability. Machine learning algorithms analyze structural data and identify promising molecular linkers and frameworks tailored to capture CO_2 efficiently. This process, combining AI›s speed with computational simulations, allows for rapid screening and refinement of material designs, enhancing the discovery pipeline for carbon capture solutions.

Metal-organic frameworks (MOFs) are advanced porous materials gaining attention for their potential in gas storage, separation, and catalysis. Their high surface area, tunable pore size, and chemical versatility make MOFs particularly effective for capturing and storing carbon dioxide (CO_2), presenting a viable approach to mitigate greenhouse gas emissions. Traditional methods for identifying optimal MOF structures face challenges due to the vast chemical space and the complexity of synthesizing and testing numerous potential candidates. Emerging AI-based frameworks leverage generative models to accelerate the design of MOFs. By focusing on CO_2 adsorption properties and using machine learning, the framework identifies promising MOF candidates through a computationally efficient process. This novel AI-guided approach could significantly enhance the pace of discovering sustainable materials for environmental applications, providing a scalable solution for carbon capture in industrial settings.

Tech Signal

Achieving a Carbon Capture Breakthrough Using AI and Supercomputers

In a new paper published in Nature Communications Chemistry, the research team›s open-source framework has identified six promising candidates for carbon capture that merit further investigation.

The AI model developed by the researchers explores an expansive range of potential chemical structures that could be used to develop materials known as metal-organic frameworks (MOFs), pinpointing promising structures for further examination. After the model generated tens of thousands of potential candidates, the team conducted computational tests to assess their physical properties and their ability to capture carbon molecules.

Metal-organic frameworks are modular materials composed of three types of building blocks: inorganic nodes like zinc or copper, organic nodes, and molecular linkers made up of carbon, oxygen, and other elements. The AI model, trained on a dataset of hypothetical metal-organic frameworks, proposed new molecular linkers expected to have high capacity for carbon capture from the air.

Overall, the model created 120,000 possible structures. Further tests eliminated those with unlikely physical or chemical properties or those too complex or costly to produce. The researchers used computer models to predict each structure›s carbon capture potential, and the top 364 candidates underwent comprehensive 3D molecular dynamics simulations to assess their structural characteristics.

The research team developed a series of analytical steps, gradually decreasing the role of AI while increasing the focus on physics and chemistry. This approach allowed them to evaluate the organic molecules based on their chemical validity, ease of synthesis, and stability.

Ultimately, the researchers identified the six most promising structures, which can be synthesized in laboratories and tested in real-world experiments. The data from these computational tests will be fed back into the AI model to generate even more effective candidates in future iterations.

The entire framework, from AI modeling to 3D simulations, can be completed within 12 hours using modern supercomputing resources. The framework, including all its components, will be open-source, available for the scientific community to replicate or adapt for other applications involving metal-organic frameworks.

The computational work supporting the paper was carried out at the Argonne Leadership Computing Facility and the National Center for Supercomputing Applications at the University of Illinois Urbana-Champaign, funded by grants from the Department of Energy and the National Science Foundation.

For more information, click here

Economic Overview

The rapid expected growth in (CCS) market reflects the growing adoption of CCS technologies to mitigate carbon emissions from industrial processes and energy production. The market expansion is likely driven by global commitments to reduce greenhouse gas emissions, advancements in CCS technology, and increased policy support aimed at achieving climate goals and transitioning toward a low-carbon economy.

The carbon capture and storage (CCS) market (Billion USD)
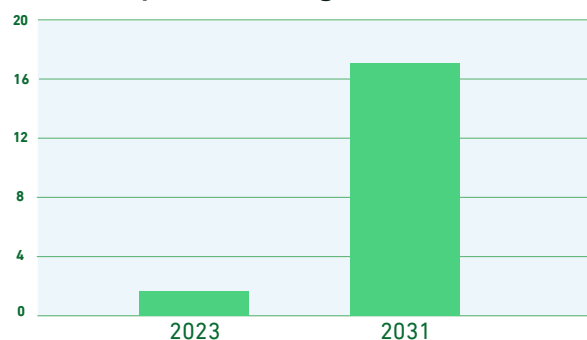
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Ensuring Environmental Sustainability", specifically by:
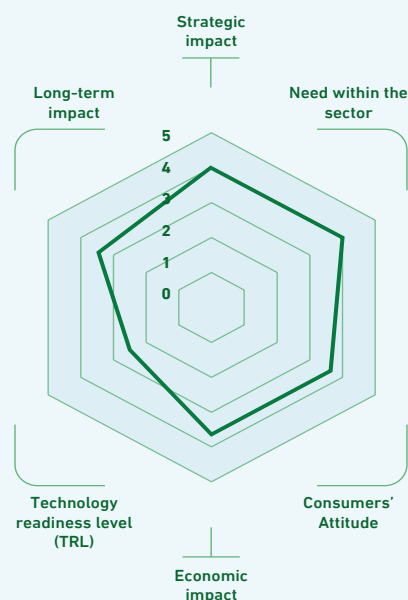
▪Reducing various types of pollution.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

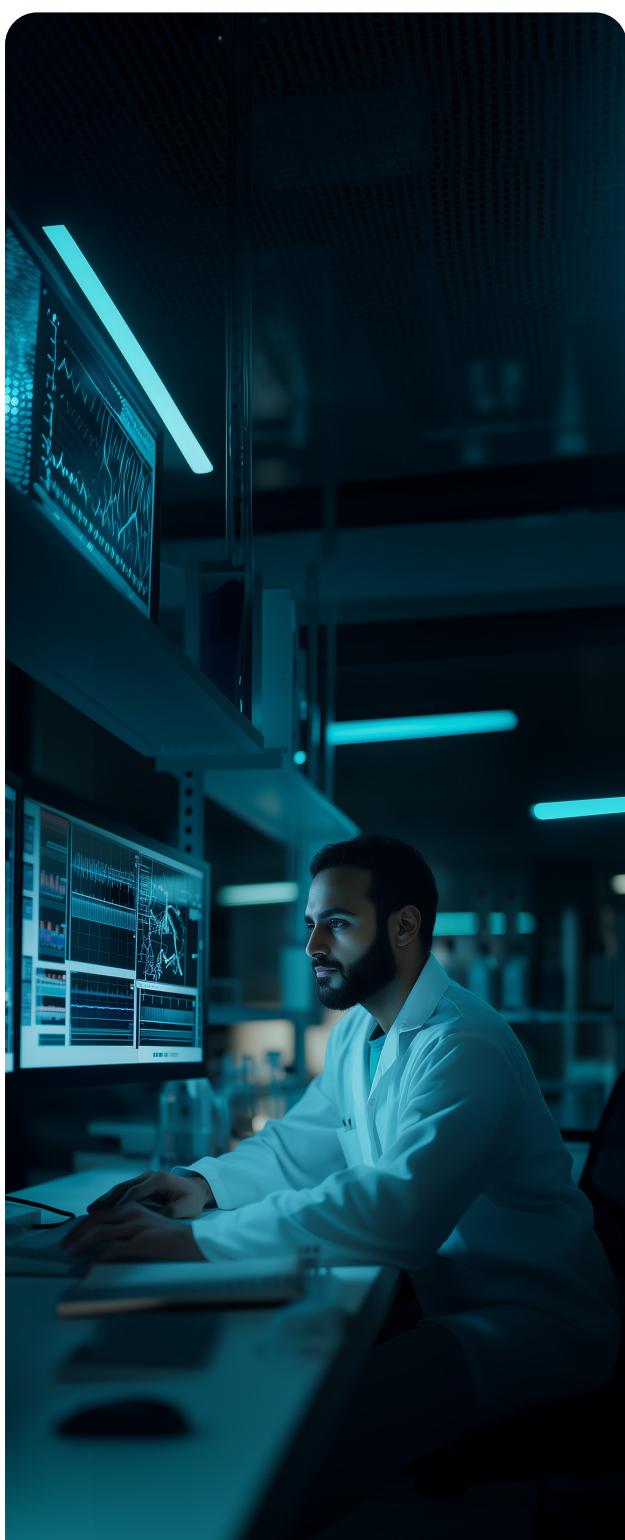▪Achieve net-zero emissions by 2060.

For more information, click here

Multi-Dimensional Evaluation

Advanced Carbon Capture Materials

07

Developing Catalysts for Environmental Protection

As global industrial activities continue to expand, environmental pollution remains a critical challenge, particularly due to the presence of persistent organic pollutants (POPs). POPs, such as polychlorinated dibenzo-p-dioxins and dibenzofurans, are among the most harmful contaminants due to their toxic, carcinogenic properties and their ability to remain in the environment for extended periods. These pollutants originate from various sources, including industrial waste, pesticide usage, and incomplete combustion processes. Because of their durability and resistance to natural degradation, they accumulate in ecosystems, posing severe threats to human health, wildlife, and overall environmental stability.

Traditional methods for eliminating these pollutants, such as catalytic oxidation, have been widely utilized; however, they often suffer from significant limitations. The conventional catalysts employed in these processes typically require high operational temperatures to achieve effective degradation, leading to increased energy consumption and costs. Moreover, these methods may not always provide the necessary efficiency in environments with fluctuating temperatures or complex contaminant mixtures. Additionally, many of the commonly used catalytic materials, such as carbon nanotubes or activated carbons, while effective in enhancing the catalytic process, come with high production costs and maintenance issues, further complicating their practical applications on a larger scale.

In recent years, researchers have been exploring more sustainable and cost-effective alternatives to address these limitations. One promising avenue is the use of biomass-derived materials, which are abundant, renewable, and can be engineered to exhibit desirable properties for catalytic applications. Nitrogen-doped carbon materials, derived from biomass sources, have emerged as a particularly promising candidate due to their large surface area, high porosity, and the ability to enhance catalytic activity at lower temperatures. These materials can be modified to increase the number of active sites available for chemical reactions, thus boosting the efficiency of pollutant degradation processes.

Recent breakthroughs, such as the development of catalysts incorporating nitrogen-doped biomass carbon, represent a significant step forward in this field. By enhancing the performance of vanadium-based catalysts, these new materials provide a more effective and economical approach to breaking down persistent organic pollutants, like furan, at lower temperatures. Such advancements highlight the potential of biomass-derived materials in improving the efficiency of environmental remediation efforts while reducing costs and energy consumption.

As research progresses, the application of these innovative catalysts could revolutionize pollution control technologies, supporting global efforts to achieve sustainable environmental management and protection.

A promising future of nitrogen-doped biomass carbon is expected for developing more sustainable and efficient catalysts for environmental cleanup, providing a scalable and economically viable approach to managing persistent organic pollutants.

For more information, click here

Tech Signal

New Biomass-Derived Catalyst for Efficient Pollution Reduction

Scientists have made significant progress in mitigating environmental pollution by enhancing vanadium-based catalysts with nitrogen-doped biomass carbon. This innovative approach improves the decomposition of furan at lower temperatures, presenting a more efficient and effective method for removing hazardous pollutants. The development represents a crucial advancement in creating sustainable and cost-efficient strategies for environmental protection.

Polychlorinated dibenzo-p-dioxins and dibenzofurans are known for their high toxicity, carcinogenic potential, and long-lasting presence in the environment. Traditional catalytic oxidation methods used to eliminate these pollutants often encounter challenges such as high operational costs and reduced effectiveness at lower temperatures. Studies have shown that incorporating carbon materials, like carbon nanotubes and activated carbons, can enhance catalytic performance by increasing the adsorption capacity and improving the dispersion of active sites on the catalyst surface. However, the practical use of these materials is constrained by high costs and the need for frequent maintenance.

Nitrogen-doped carbon materials derived from biomass offer a promising alternative due to their large surface area and high porosity, which can potentially lower the operating temperatures and boost the overall efficiency of the catalytic process. Researchers from Zhejiang University have developed a new catalyst utilizing nitrogen-doped biomass carbon to improve the degradation of harmful pollutants at lower temperatures. This breakthrough is documented in a study that showcases a sustainable and cost-effective strategy for addressing environmental pollution, highlighting the potential of biomass-derived materials in enhancing environmental conservation efforts.

The study, published in the journal Waste Disposal & Sustainable Energy, presents a novel catalyst combining vanadium-based components with nitrogen-doped hierarchical porous carbon (NHPC). This innovative material significantly improves the low-temperature breakdown of furan, providing an effective solution for the degradation of persistent organic pollutants and marking a significant advancement in environmental cleanup efforts.

The research team developed several vanadium-based catalysts whose performance was significantly enhanced by the incorporation of nitrogen-doped hierarchical porous carbon derived from biomass. The addition of NHPC led to a notable improvement in the catalytic degradation of furan, a stubborn organic pollutant, at lower temperatures than previously achievable. The inclusion of NHPC increased the number of active sites and promoted a more uniform distribution of vanadium oxide phases, both of which are essential for efficient catalytic activity. The modified catalyst achieved a 50% conversion rate of furan at 150 °C, a significant improvement compared to traditional catalysts, and complete conversion was observed at 200°C.

This advancement not only enhances the efficiency of furan degradation at substantially lower temperatures but also opens new avenues for sustainable environmental remediation practices. The use of nitrogen-doped hierarchical porous carbon in catalysts represents a major breakthrough in environmental technology, offering a low-temperature, cost-effective method for the removal of hazardous pollutants. This innovation sets a new benchmark for pollution control and underscores the potential of biomass-derived carbon materials in catalytic degradation, improving pollutant removal efficiency and promoting sustainable environmental protection solutions.

For more information, click here

Economic Overview

The figure illustrates the steady growth of the environmental catalysts market, which reflects the rising demand for sustainable solutions to reduce industrial emissions and pollutants. Environmental catalysts play a crucial role in facilitating cleaner production processes, enhancing air and water quality, and supporting global environmental regulations.

The environmental catalysts market (Billion USD)
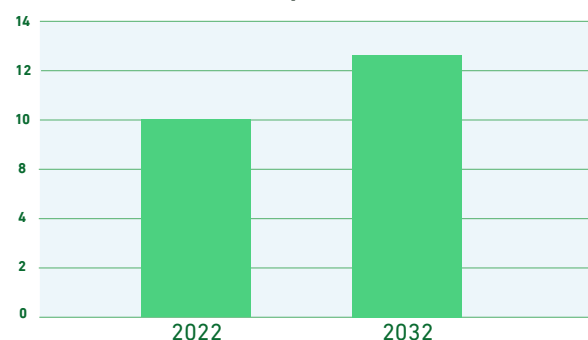
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Ensuring Environmental Sustainability", specifically by:

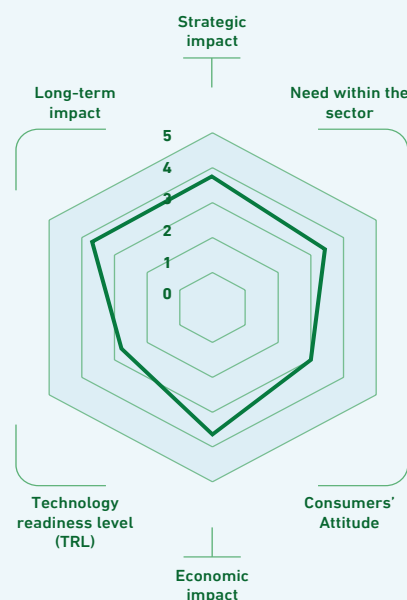▪Protecting the environment from natural hazards (such as desertification).

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

▪Protect 30% of the Kingdom›s land and sea by 2035.

For more information, click here

Multi-Dimensional Evaluation

Developing Catalysts for Environmental Protection

08

Elastocalorics for Cooling and Heating Applications

Elastocaloric materials are materials that exhibit a significant temperature change when stress is applied or removed. This phenomenon is known as the elastocaloric effect. When elastocaloric materials are subjected to stress, they absorb heat, which cools down their surroundings. Conversely, when the stress is released, they release heat, which heats up their surroundings. This ability to absorb and release heat can be harnessed to develop solid-state heating and cooling systems. These systems provide efficient and environmentally-friendly alternatives to traditional vapor-compression systems, which are currently used in most refrigerators and air conditioners.

Elastocaloric systems are potentially more efficient as they do not require a compressor. Compressors are energy-intensive devices that use a lot of electricity. Traditional vapor-compression systems often use refrigerants that contribute to greenhouse effect and climate change, whereas elastocaloric systems are more environmentally friendly as they eliminate the need for harmful refrigerants. However, their life cycle impacts require further investigation.

Elastocaloric-based technologies have the potential to significantly improve the efficiency and sustainability of heating and cooling systems. Researchers are still working on developing elastocaloric materials with the right properties for practical applications.

Elastocaloric technology, which leverages the elastocaloric effect in certain materials to achieve cooling, holds significant promise for applications in air conditioning and heat pump systems. Traditional heat pumps and air conditioners, which rely on vapor-compression cycles, are responsible for approximately 17% of global electricity consumption. By contrast, elastocaloric systems offer the potential for higher energy efficiency and eliminate the environmental risks associated with refrigerant leakage, as they do not require harmful refrigerants.

This makes elastocaloric technology a compelling alternative for sustainable cooling solutions. In addition to residential and commercial air conditioning, elastocaloric systems could find use in refrigeration, industrial cooling processes, and even electronic device cooling. The ability to scale elastocaloric systems from small to large applications, combined with their potential for miniaturization, could make them vital for various industries.

A particularly intriguing possibility is the integration of elastocalorics into portable cooling devices. Wearable cooling technologies powered by elastocaloric systems could significantly improve personal comfort while reducing the energy demands of larger, centralized air conditioning systems. This flexibility positions elastocalorics as a promising technology where precise temperature control is essential.

Elastocaloric technology promises to revolutionize systems like heat pumps and air conditioning, offering both enhanced efficiency and a lower environmental footprint. Elastocalorics stands at the forefront of a new era in cooling and heating technologies. With the promise of high efficiency, reduced environmental impact, and versatility across applications, elastocaloric systems have the potential to replace conventional technologies and reshape the thermal management landscape. As research continues to address current challenges -such as: life cycle environmental impact assessment, resources, energy efficiency, scalability and cost-, elastocalorics may soon become a household name, leading the way toward a more sustainable, energy-efficient future.

For more information, click here

|01| |02| |03| |04| |05| |06|

Tech Signal

Revolutionizing Cooling and Heating Techniques with Elastocalorics

Elastocalorics is based on a unique thermodynamic process where a material absorbs or releases heat as it undergoes mechanical stress or strain. The phenomenon is rooted in the material's phase transformation, where certain solid-state materials, known as shape-memory alloys (SMAs), exhibit a large temperature change when mechanically deformed and then returned to their original shape. This elastocaloric effect can be harnessed for efficient heating and cooling applications.

Unlike traditional refrigeration or air conditioning systems, which rely on vapor-compression cycles and chemical refrigerants, elastocaloric systems use solid materials to induce temperature changes through mechanical means. This solid-state process avoids the use of harmful refrigerants like hydrofluorocarbons (HFCs), which are potent greenhouse gases. The ability to achieve cooling without harmful refrigerants makes elastocaloric technology an eco-friendly alternative.

A research team from the University of Maryland has published a paper discussing elastocaloric cooling, a technology that offers an energy-efficient alternative to traditional vapor compression systems, harnessing the latent heat from the phase transition in shape memory alloys. It reviews the thermodynamics of elastocaloric cycles, materials used, and advancements in system performance, including heat transfer and actuator mechanisms. The authors introduce a non-dimensional performance parameter to evaluate prototypes and discuss strategies to enhance future device efficiency. Overall, the paper highlights elastocaloric cooling›s potential as a sustainable cooling technology. This research was supported by U.S. DOE (Department of Energy).

The core of elastocaloric systems lies in materials such as nickel-titanium (NiTi) alloys, which can absorb and release significant amounts of thermal energy during mechanical deformation. When the material is mechanically compressed or stretched, it undergoes a phase change that leads to a substantial temperature drop. This temperature change can be reversed when the material returns to its original shape, enabling a cyclical process of heat absorption and rejection.

In practical applications, these elastocaloric materials are arranged in systems where mechanical stress is cyclically applied, allowing them to continuously cool or heat a medium such as air or water. This process can achieve efficiencies that rival or exceed traditional vapor-compression refrigeration technologies, making it a highly attractive option for the future of thermal management.

One of the key advantages of elastocaloric technology is its potential for high efficiency. A research team from the University of Naples Federico II has published a study in International Journal of Refrigeration highlighting that elastocaloric systems can achieve energy efficiencies up to 50% higher than traditional systems due to the direct transfer of mechanical energy into thermal energy. Moreover, the elimination of harmful refrigerants reduces both the environmental and regulatory concerns associated with conventional cooling technologies.

In regions where energy infrastructure is strained, elastocaloric systems could play a vital role in ensuring energy security while meeting the growing demand for cooling. Furthermore, the versatility of elastocaloric systems, which can both cool and heat spaces depending on the phase transformation, makes them a highly adaptable solution for climates with extreme temperature variations.

For more information, click here

Economic Overview

The upward trend shown in the figure highlights the growing adoption of solid-state cooling technologies, driven by advancements in energy-efficient systems and environmentally friendly alternatives to traditional refrigeration and cooling methods. The market›s growth reflects the increasing demand for sustainable solutions in both residential and industrial cooling applications.

The environmental catalysts market (Billion USD)
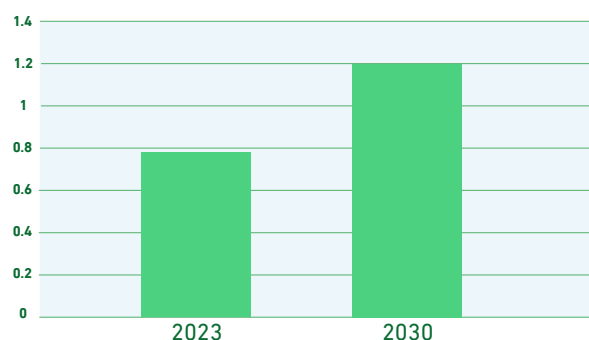
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Unleashing the potential of promising non-oil sectors", specifically by:

▪ Localization of promising industries.

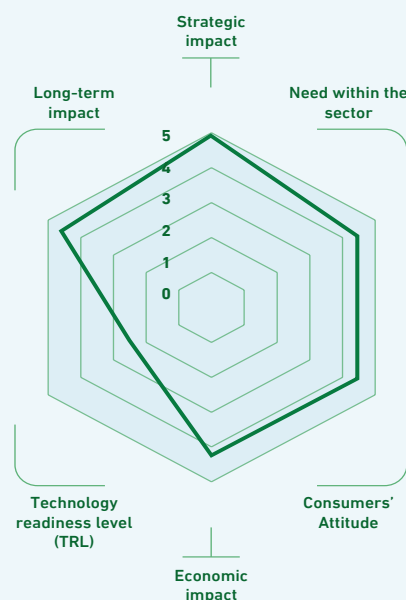## Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

▪ Develop and adopt innovative cooling technologies to reduce cooling electricity consumption by 30% by 2040.

For more information, click here

|01|　　|02|

Multi-Dimensional Evaluation

Elastocalorics for Cooling and Heating Applications

09

Cooling Cities with Supercooling Materials

Scientists are developing innovative technologies to protect cities from dangerous heat as global temperatures continue to rise. With recent years setting records for high temperatures worldwide, urban areas face significant challenges such as increased heat stress which results in around 500,000 deaths annually . Consequently, researchers are focusing on cooling solutions, from highly efficient air conditioners to special materials that lower temperatures without relying on electricity.

Traditional air conditioners consume significant energy and emit greenhouse gases (GHGs), prompting the development of more efficient alternatives. One such innovation is the «electrocaloric» cooling device developed at the Luxembourg Institute of Science and Technology. This technology uses an electric field to manipulate the atomic structure of insulating ceramics, resulting in cooling without environmentally harmful refrigerants. Although promising, the technology›s commercialization may take time, with initial applications potentially targeting cooling batteries in electric cars.

Another breakthrough involves supercool materials that can keep surfaces cooler than their surrounding environment without using electricity. These materials reflect most of the sunlight and emit a significant amount of thermal radiation, effectively cooling themselves and the air around them. First developed in 2014 at Stanford University, these materials have since been expanded into various forms, including plastics, metals, paints, and even wood.

Supercool materials could significantly reduce urban temperatures and decrease the demand for air conditioning. For example, a team at Stanford developed a physical mechanism using specific coatings that adapt to seasonal temperature changes, optimizing thermal comfort throughout the year. Similarly, researchers at Columbia University applied supercool paint selectively on building surfaces to maintain cooler temperatures. Urban planners are also testing reflective «cool pavements,» which have shown a measurable cooling effect in city environments. It is worthy to mention that road cooling techniques were applied successfully during the Hajj.

Shape-shifting materials represent another exciting avenue of research. A team at the University of Melbourne has developed phase-change inks that alter their structure based on temperature, reflecting or absorbing heat as needed. This adaptable technology could improve building energy efficiency, particularly in climates where temperature extremes are common.

For more information, click here

Tech Signal

Innovative Technologies to Shield Cities from Extreme Heat

Riyadh, located in a desert region and one of the hottest cities globally, is experiencing increased heat levels due to climate change and rapid urban growth. The city's limited vegetation and extensive artificial surfaces like asphalt and concrete contribute to trapping heat, exacerbated by emissions from vehicles and industrial activities.

Research published in Nature Cities, the research presents a comprehensive approach using ‹super cool› materials, enhanced vegetation, and energy-efficient retrofitting to mitigate urban heat. This study, conducted in collaboration with the Royal Commission of Riyadh, is the first to explore the extensive energy benefits of these advanced cooling technologies when applied on a city-wide scale. The study emphasizes the significant impact these methods can have in reducing urban temperatures, lowering cooling energy demands, and improving public health and well-being.

To identify optimal strategies for cooling Riyadh, the research team conducted large-scale simulations of climate and energy use, analyzing the effects of different combinations of cooling materials, vegetation, and retrofitting measures on over 3,300 buildings. The results showed that employing these methods could reduce outdoor temperatures by almost 4.5°C in summer and improve energy conservation by up to 16%.

The research also found that retrofitting buildings with advanced cooling technologies, such as improved insulation, windows, and roofs, could cut cooling energy demands by up to 35%, significantly reducing the city›s energy consumption and associated costs. The study suggests to implement this tailored heat mitigation plan, which would be the largest of its kind globally, promising considerable health, sustainability, and economic benefits for the city›s future.

However, challenges remain in scaling these technologies from the lab to widespread urban use. Questions about their efficacy in various climates, potential drawbacks, and consumer acceptance still need to be addressed. For instance, while cool pavements effectively reduce surface temperatures, they may not be suitable for all locations due to their reflective properties, which can cause discomfort for people spending extended periods outdoors. Additionally, the performance of supercool materials can vary depending on humidity and cloud cover, which affects their ability to radiate heat into space.

Despite these uncertainties, cities worldwide are beginning to experiment with these cooling technologies. Los Angeles, for example, is aiming to increase its cool surface coverage by 30% by 2045, while Riyadh has started implementing a multifaceted strategy to reduce urban temperatures by up to 4.5°C. This strategy includes retrofitting buildings with cool and supercool materials and expanding green spaces.

Overall, the demand for innovative cooling solutions is growing, with more industrial producers entering the market. These advancements offer promising potential to protect urban areas from extreme heat, mitigate energy consumption, and enhance the overall quality of life for city dwellers in a warming world.

For more information, click here

|01| |02|

Economic Overview

The figure highlights the significant growth expected in the advanced phase change materials (PCM) market, which underscores the increasing adoption of PCMs in various applications, such as building energy efficiency, temperature regulation in electronics, and thermal energy storage.

The advanced phase change materials market (Billion USD)
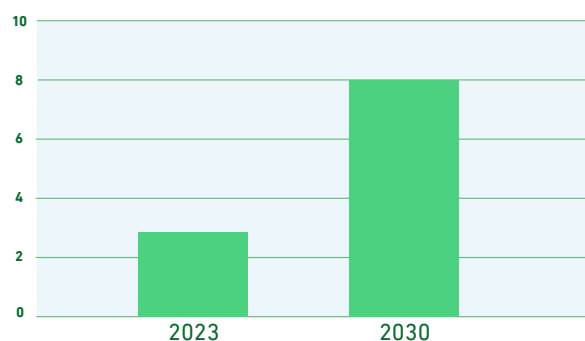
Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Unleashing the potential of promising non-oil sectors", specifically by:
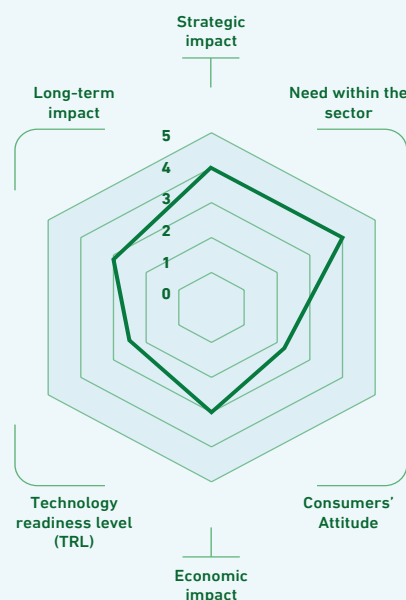
- Localization of promising industries.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Reduce summer surface temperatures by 4°C by 2040.

For more information, click here

Multi-Dimensional Evaluation

Cooling Cities with Supercooling Materials

10

AI-Enhanced Climate Change Monitoring

Advances in climate change monitoring have become increasingly critical as the world faces accelerating changes in weather patterns, ocean temperatures, and ecosystem disruptions. Recent developments in technology, data collection, and predictive analytics are revolutionizing how scientists and policymakers understand and respond to climate change. With the continuous enhancement of satellite technology, remote sensing, and data integration, monitoring has become more precise, enabling real-time analysis and forecasting of climatic conditions across the globe. This progress plays a pivotal role in identifying trends, predicting future scenarios, and developing actionable strategies to mitigate and/or adapt the impacts of climate change.

One of the most significant advances in climate change monitoring is the use of satellite-based remote sensing. Agencies such as NASA and the European Space Agency (ESA) have launched sophisticated satellites like Landsat, Copernicus, and the Sentinel series, which provide critical data on atmospheric, oceanic, and terrestrial changes. These satellites monitor a wide range of climate indicators, including greenhouse gas emissions, sea level rise, ice sheet dynamics, and land cover changes.

Machine learning (ML) and artificial intelligence (AI) also play a transformative role in enhancing climate monitoring. These technologies enable researchers to process vast amounts of environmental data quickly, detecting patterns and anomalies that may not be visible through conventional analysis. For example, ML algorithms are increasingly applied to analyze satellite images, automate climate trend identification, and improve predictive models of extreme weather events such as hurricanes, wildfires, and floods. The integration of AI in climate monitoring accelerates data interpretation, allowing faster response to emerging climatic threats and enhancing the effectiveness of early warning systems.

Advancements in sensor technologies have further improved climate data collection. Innovations in in-situ sensors, such as ocean buoys, weather stations, and drones, complement satellite data by providing high-resolution, localized information. These sensors capture a detailed view of temperature, humidity, atmospheric pressure, and other variables in real time. The deployment of smart sensors in remote or extreme environments, like polar regions and rainforests, has allowed researchers to gather insights on ecosystems previously difficult to monitor. This data is vital for studying the effects of climate change on biodiversity and ecosystem resilience.

Agencies like the European Centre for Medium-Range Weather Forecasts (ECMWF) are already adopting AI-based forecasts, while others are developing their own. Although these models still have limitations, such as difficulty in predicting hurricane intensity, they are expected to improve, especially as they incorporate direct observational data. AI's speed also allows for numerous runs, which can help capture atmospheric uncertainties.

If early warning systems are successfully developed, they could offer valuable lead time to adapt to these changes. This could involve building seawalls, relocating cities, or preparing for shifts in food production and supply chains. Additionally, more reliable predictions might spur discussions on large-scale engineering interventions, such as stabilizing glaciers or releasing particles into the atmosphere to reflect sunlight away from Earth, known as solar geoengineering.

For more information, click here

|01| |02| |03|

Tech Signal

Developing an Alarm System for Climate Tipping Points

The UK has launched an £81 million program to develop early warning systems for climate tipping points, under the direction of the Advanced Research and Invention Agency (ARIA). This initiative focuses on two crucial tipping points: the rapid melting of the Greenland Ice Sheet and the weakening of the North Atlantic Subpolar Gyre. These tipping points could cause irreversible changes in global ecosystems, significantly affecting sea levels, weather patterns, and human societies. ARIA›s program seeks to reduce the uncertainty surrounding these tipping points by developing low-cost sensors, deploying observational networks, and creating advanced computer models to detect early warning signs.

The Greenland Ice Sheet, which has been melting at increasing rates due to accelerated Arctic warming, poses a significant threat. If it collapses entirely, global sea levels could rise by over 20 feet (6 meters), displacing millions of people and causing mass climate migration. In addition to rising sea levels, the influx of freshwater into the North Atlantic from the melting ice could slow down key ocean currents, including the Subpolar Gyre, which plays a vital role in regulating global climate patterns. A weakened Gyre could lead to erratic weather and disruptions to agriculture and fisheries.

ARIA's tipping points program aims to create affordable, sustainable, and scientifically sound early warning systems. Such systems do not exist today, though significant research has been done on climate tipping points. The goal is to improve understanding of when these tipping points might be crossed, what effects they would have, and how long those effects might last. The agency will fund research teams to develop sensors capable of operating in harsh environments, deploy them in monitoring networks, and use data-driven models to detect subtle signals of impending tipping points. However, this is a challenging task given the limited historical data and the complexity of these climate systems.

The ARIA program, which draws inspiration from the US's DARPA and ARPA-E, seeks to push the boundaries of what is possible in scientific research. While some experts question the focus on the Subpolar Gyre over other tipping points like AMOC, ARIA's leaders believe that the effort is necessary. They hope that the program will attract researchers from diverse fields, including those not traditionally involved in climate science, and that it will engage local communities and governments in Greenland, where much of the research will be focused.

Ultimately, while the challenge is immense, ARIA's research into early warning systems for climate tipping points could provide crucial insights and tools for mitigating the worst effects of climate change. Even if the systems themselves remain difficult to achieve, the knowledge gained from the program could have far-reaching implications for how humanity prepares for a rapidly changing planet.

Also, the United Nations is utilizing AI in Africa as part of a project aimed at supporting climate-vulnerable communities. The IKI Project employs AI technology to forecast weather patterns, enabling communities and local authorities to better prepare for and adapt to the effects of climate change. The initiative focuses on enhancing access to clean energy, establishing effective waste management systems, and promoting reforestation efforts.

For more information, click here

Economic Overview

The figure illustrates the projected growth of the environmental monitoring market. This growth reflects the rising global focus on monitoring and managing environmental parameters to address challenges such as climate change, pollution control, and resource conservation.
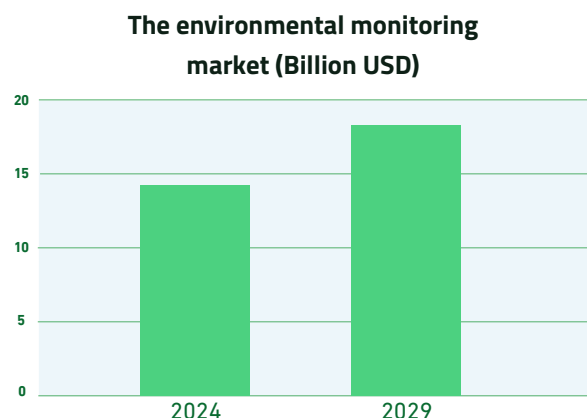
The environmental monitoring market (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through "Ensuring Environmental Sustainability", specifically by:

▪ Protecting the environment from natural hazards (such as desertification)..
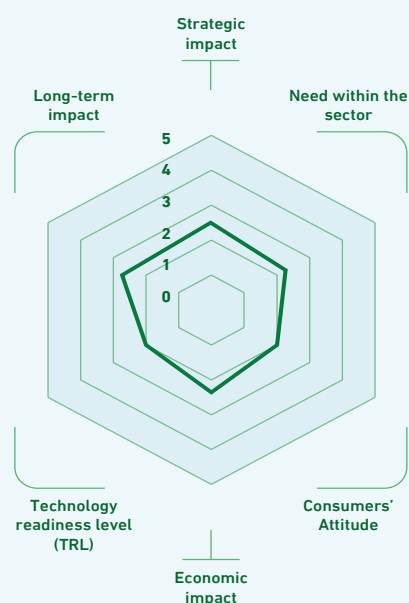
Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

▪Protect 30% of the Kingdom›s land and sea by 2035.

For more information, click here

|01| |02| |03|

Multi-Dimensional Evaluation

Climate Change Monitoring

04
CONCLUSION

The transformative role of technology foresight in Research, Development, and Innovation (RDI) planning is pivotal for addressing today's environmental challenges and essential resource needs. By anticipating future demands and exploring breakthrough technologies, foresight helps guide sustainable innovation toward impactful outcomes. This report has presented ten emerging technologies with the potential to revolutionize sustainable practices and supply essential resources efficiently.

Elastocalorics provide a novel solution for cooling and heating with reduced environmental impact, exemplifying how alternative approaches can mitigate energy challenges. Advanced water purification using hydrogels and nanobubble technology offers scalable solutions to water scarcity by improving filtration and recycling processes. These technologies are particularly essential in regions where water is limited, enhancing resilience in resource-stressed areas. AI-driven agriculture and biotechnology innovations support more productive, resource-efficient farming practices, addressing global food security and reducing agriculture's environmental footprint.

Carbon capture materials optimized by artificial intelligence show significant promise in reducing atmospheric CO_2 levels, crucial in the fight against climate change. Meanwhile, reflective materials for cooling urban areas and AI-based water quality monitoring provide tools to mitigate local and global environmental impacts. These innovations, alongside novel catalysts for pollution reduction, underscore how targeted RDI efforts contribute to both immediate and long-term sustainability goals.

Climate change monitoring, bolstered by advanced data analysis, remains fundamental for understanding and adapting to environmental shifts. Together, these technologies illustrate a comprehensive approach to sustainability, where innovation is grounded in addressing both present and anticipated challenges.

The emerging technologies explored in this report represent a promising pathway to a sustainable future. Technology foresight will continue to be instrumental in guiding these advancements, ensuring that RDI initiatives prioritize the environment and essential resources. By supporting these innovations, we can build resilient systems that fulfill essential needs while preserving the planet for future generations, ultimately creating a more sustainable and equitable world.