Scientific
Research
Publishing

Journal of Applied Mathematics and Physics, 2024, 12, 2506-2558
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Innovative Technologies for Large-Scale Water Production in Arid Regions: Strategies for Sustainable Development

Boris Menin

Beer-Sheva, Israel
Email: meninbm@gmail.com

How to cite this paper: Menin, B. (2024) Innovative Technologies for Large-Scale Water Production in Arid Regions: Strategies for Sustainable Development. *Journal of Applied Mathematics and Physics*, **12**, 2506-2558.
https://doi.org/10.4236/jamp.2024.127150

Received: June 16, 2024
Accepted: July 20, 2024
Published: July 23, 2024

Abstract

Water scarcity in arid regions poses significant challenges to sustainable development and human well-being. This article explores both existing and innovative technologies and methods to produce large amounts of water to address these challenges effectively. Key approaches include atmospheric water generation, advanced desalination techniques, innovative water collection methods such as fog nets and dew harvesting, geothermal water extraction, and water recycling and reuse. Each method is evaluated for its feasibility with existing technology, potential time of implementation, required investments, and specific challenges. By leveraging these technologies and combining them into a multifaceted water management strategy, it is possible to enhance water security, support agricultural and industrial activities, and improve living conditions in arid regions. Collaborative efforts between governments, private sector entities, and research institutions are crucial to advancing these technologies and ensuring their sustainable implementation. The article provides a comprehensive overview of the current state of these technologies, their potential for large-scale application, and recommendations for future research and development.

Keywords

Atmospheric Water Generation, Advanced Desalination, Sustainable Development, Geothermal Water Extraction, Water Recycling, Arid Regions, Water Security

1. Introduction: The Imperative of Water Production in Arid Regions

Water scarcity in arid regions is a formidable challenge that undermines sustainable development, economic growth, and human well-being. The severe lack of accessible fresh water disproportionately affects arid and semi-arid regions, exacerbating poverty, hindering development, and escalating tensions over limited water resources. In these regions, the hydrological cycle is disrupted by meager precipitation and high rates of evaporation, leading to perennial water shortages.

1.1. Overview of Water Scarcity Challenges

Arid regions, characterized by low rainfall and high evaporation, are especially vulnerable to water scarcity. This situation is further compounded by climate change, population growth, and escalating demands for water from agriculture, industry, and domestic use. The United Nations estimate that by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be under water-stressed conditions [1].

Climate Change: The impact of climate change on water resources cannot be overstated. Rising temperatures increase evaporation rates, reducing available surface and groundwater, while climate models predict more frequent and severe droughts in arid regions, straining scarce water resources [2]. For example, in the Middle East and North Africa (MENA) region, climate-induced water stress is predicted to escalate, exacerbating socio-economic vulnerabilities in areas already facing political instability and resource scarcity [2].

Population Growth: Rapid population growth in arid regions increases the demand for water, placing further stress on limited water supplies. Urbanization and industrialization contribute to higher water consumption, while agricultural practices, which account for approximately 70% of global water use, continue to demand vast quantities of water (UNESCO, 2021). For example, sub-Saharan Africa and South Asia, regions with significant arid and semi-arid areas, are expected to witness continued population growth, intensifying water scarcity challenges [3].

Agricultural Demands: The agriculture sector is the largest consumer of fresh water globally, and this trend is even more pronounced in arid regions where irrigation is essential for food production. Traditional irrigation methods are often inefficient, leading to significant water losses through evaporation and runoff. In countries like India and Pakistan, inefficient water use in agriculture exacerbates water scarcity, affecting both food security and economic development [4].

Water Pollution: Industrial, agricultural, and domestic pollution further degrades water quality, making the available water unsafe for consumption and use in agriculture and industry. The presence of contaminants such as heavy metals, nitrates, and pathogens in water bodies limits the usability of these resources, necessitating costly treatment processes. For instance, water pollution in China's arid regions poses a significant challenge, not only depleting usable water resources but also requiring substantial investments in water purification technologies [5].

Transboundary Water Conflicts: Many rivers and aquifers cross national boundaries, leading to potential conflicts over water rights and usage. In arid regions, the competition for shared water resources can exacerbate tensions between neighboring countries. The Nile Basin and the Jordan River Basin are classic examples where water scarcity has led to diplomatic tensions and the need for international water-sharing agreements [6].

Economic Impacts: The economic consequences of water scarcity in arid regions are profound. Industries reliant on water, including agriculture, mining, and manufacturing, face operational challenges and increased costs, reducing economic productivity and growth. For example, the California drought (2012-2016) resulted in significant economic losses, particularly in the agricultural sector, highlighting the vulnerability of economies to water scarcity [7].

Health Implications: Limited access to clean water has dire health implications, including higher incidences of water-borne diseases and malnutrition. Health facilities in arid regions often struggle to provide adequate care due to water shortages, exacerbating public health crises. In sub-Saharan Africa, for instance, inadequate water supply and sanitation services contribute to high rates of diarrheal diseases, which remain a leading cause of child mortality [8].

Given these multifaceted challenges, addressing water scarcity in arid regions requires innovative and sustainable approaches to water production and management. Traditional methods such as dams and reservoirs, while useful, have limitations in terms of environmental impact and long-term viability. On the other hand, emerging technologies that enhance water production, such as advanced desalination, atmospheric water generation, and water recycling, offer promising solutions that can be integrated into a comprehensive water management strategy.

To tackle the intricacies of water scarcity, it is imperative to assess the feasibility, scalability, and sustainability of new technologies alongside existing methods. Such an integrated approach will not only alleviate water scarcity but also enhance resilience against future climatic and demographic changes, ensuring sustainable development in arid regions.

1.2. Importance of Sustainable Water Production

Sustainable water production methods, like rainwater harvesting, managed aquifer recharge, and advanced irrigation techniques, protect and preserve natural ecosystems, ensuring essential services such as water purification, habitat for species, and carbon sequestration. The concept of sustainability in water production encompasses various dimensions, including ecological balance, economic feasibility, social equity, and resilience to climate change. Each of these dimensions contributes to the overarching goal of maintaining water resources for future generations while meeting the needs of the present. This subchapter delves into the multifaceted importance of sustainable water production with particular emphasis on its role in ecological preservation, economic stability, social development, and climate resilience.

1.2.1. Ecological Balance

One of the primary reasons for the importance of sustainable water production is maintaining ecological balance. Unsustainable water extraction and management practices can lead to significant environmental degradation, including the depletion of aquifers, reduction in river flows, and loss of wetlands. These ecological changes can have cascading effects on biodiversity, soil stability, and local climate patterns (Vörösmarty *et al.*, 2010). For instance, the Aral Sea in Central Asia has dramatically shrunk due to unsustainable water withdrawal for irrigation, leading to the loss of aquatic and terrestrial ecosystems and creating a local environmental catastrophe [9].

Sustainable water production methods, such as rainwater harvesting, managed aquifer recharge, and advanced irrigation techniques, help protect and preserve natural ecosystems. By balancing water extraction with natural replenishment rates and minimizing environmental impacts, these methods ensure that ecosystems can continue to provide essential services, such as water purification, habitat for species, and carbon sequestration.

1.2.2. Economic Feasibility

Economically, sustainable water production is vital for the stability and growth of industries that rely heavily on water, such as agriculture, energy, and manufacturing. Water scarcity can lead to increased costs for businesses due to the need for alternative water sources, water treatment, and efficiency measures. These increased costs can reduce profit margins and competitiveness, ultimately affecting economic development [10]. For instance, the agricultural sector in California faced significant economic losses during the 2012-2016 drought, highlighting the economic vulnerability to water scarcity [7].

Sustainable water production methods, such as drip irrigation, precision agriculture, and water recycling, can enhance water-use efficiency, reducing costs and improving resilience to water shortages. Moreover, investment in sustainable water technologies can create new economic opportunities and jobs, bolstering local and national economies. For example, the growth of the desalination industry, driven by technological advancements and increased demand, has spurred economic growth in regions like the Middle East and North Africa [11].

1.2.3. Social Equity

Access to clean and reliable water is a fundamental human right and is critical for social equity. Water scarcity disproportionately affects marginalized communities, including rural and low-income populations, who may lack the infrastructure and resources to secure adequate water supplies. Sustainable water production ensures that all segments of society have access to the water needed for drinking, sanitation, agriculture, and other essential activities.

Socially equitable water management also involves participatory governance, where local communities are involved in decision-making processes related to water resources. This approach ensures that the needs and perspectives of various stakeholders are considered, leading to more inclusive and effective water management strategies. For instance, community-based water management projects in sub-Saharan Africa have demonstrated the potential of participatory approaches to improve water access and management [12].

1.2.4. Climate Resilience

Climate change poses significant risks to water resources, with projected increases in the frequency and intensity of droughts, shifts in precipitation patterns, and altered hydrological cycles (IPCC, 2021). Arid regions are particularly susceptible to these changes, with potentially severe impacts on water availability and ecosystem health. Sustainable water production methods are essential for building climate resilience, enabling societies to adapt to the changing climate and secure water supplies under variable conditions.

For example, water-saving irrigation technologies, such as drip and sprinkler systems, can reduce water consumption and enhance productivity even under drought conditions. Similarly, rainwater harvesting systems and aquifer recharge techniques can enhance water storage and availability during dry periods, providing a buffer against climate-induced variability. Advanced desalination technologies, powered by renewable energy, offer a climate-resilient solution to water scarcity by providing a reliable source of fresh water that is not dependent on local hydrological conditions [13].

1.2.5. Integrated Water Management

An integrated approach to water management, which combines various sustainable water production methods, is crucial for addressing the complex and interrelated challenges of water scarcity. This approach involves the coordinated management of surface water, groundwater, and alternative sources, considering the ecological, economic, and social dimensions of water use. By integrating different methods, such as desalination, water recycling, and aquifer recharge, water managers can optimize water resources and enhance resilience to shocks and stresses.

Integrated water management also requires cross-sectoral collaboration and partnerships among governments, private sector entities, and research institutions. Collaborative efforts can drive innovation, mobilize resources, and enable the sharing of knowledge and best practices, ultimately leading to more effective and sustainable water management solutions [14].

1.2.6. Integrated Water Management

Continued research and development are essential for advancing sustainable water production technologies and addressing emerging challenges. Investment in research can drive technological innovations, improve efficiency and cost-effectiveness, and expand the range of available solutions. For instance, advancements in membrane technology for desalination and water reuse can significantly enhance the performance and sustainability of these methods. Furthermore, research into novel water production techniques, such as atmospheric water generation and solar-driven desalination, holds promise for future applications [15].

Sustainable water production is vital for maintaining ecological balance, supporting economic stability, promoting social equity, and building climate resilience. An integrated approach that leverages diverse methods and fosters collaboration among stakeholders can address the multifaceted challenges of water scarcity in arid regions. Continued investments in research and development are crucial for advancing sustainable water technologies and ensuring a secure water future for all.

2. Existing Methods of Fresh Water Production

This chapter reviews traditional methods of water production, including atmospheric water generation, desalination techniques, and water recycling. Each method's feasibility, efficiency, and impact on water resources are critically evaluated [7].

2.1. Atmospheric Water Generation

Atmospheric water generation (AWG) involves extracting water from ambient air, tapping into the atmospheric moisture that exists even in arid regions. Two primary methods, condensation and desiccation, have distinct advantages and challenges, including financial considerations.

2.1.1. Condensation-Based Methods

Condensation-based AWG systems function by cooling air below its dew point, causing water vapor to condense into liquid water. This process typically involves a cooling mechanism, such as a heat exchanger.

Feasibility and Efficiency: These systems are effective in high-humidity areas but become less efficient in extremely dry environments. The energy requirements for cooling can be considerable. For example, according to a study by Menon and Jiang (2017), the energy consumption of thermoelectric coolers in condensation-based AWG units is about 0.2 kWh per liter of water produced under optimal conditions [16].

Financial Data:

1) Capital Costs: The initial investment for small-scale AWG systems ranges from $1000 to $3000 per unit, sufficient to produce 5 - 10 liters of water per day (Ford & Creel, 2018) [17].

2) Operating Costs: Operating costs predominantly include electricity, maintenance, and filter replacements. At an electricity rate of $0.12 per kWh, the operating cost is approximately $0.05 - $0.10 per liter based on reported energy consumption figures [17].

3) Larger Systems: For commercial-scale systems that produce around 5000 liters per day, the initial investment can reach up to $250,000, with operating costs ranging from $0.03 to $0.07 per liter [17].

Environmental Impact: The choice of energy source greatly influences the environmental impact. Renewable energy integration, such as solar panels, can significantly reduce the carbon footprint. Menon and Jiang (2017) reported that using solar power can reduce CO_2 emissions by over 80% compared to systems powered by grid electricity [16].

Real-World Applications: Condensation-based AWG systems have been deployed in military applications and disaster relief efforts. For instance, the US military employs portable AWG units capable of producing up to 20 liters of water per day, costing approximately $1200 per unit, making them viable for emergency scenarios [18].

2.1.2. Desiccation-Based Methods

Desiccation-based AWG systems use materials known as desiccants to absorb water vapor from the air. The water is then extracted from the desiccant through a regeneration process that typically involves heating.

Feasibility and Efficiency: Desiccation-based systems can operate effectively in lower humidity conditions. The regeneration process does require energy, but advancements in material science, such as the development of metal-organic frameworks (MOFs), are improving efficiency (Hanikel *et al.*, 2019) [19].

Financial Data:

1) Capital Costs: Initial costs for small-scale desiccation-based systems range from $2500 to $5000, producing up to 10 liters of water per day [20].

2) Operating Costs: Operating costs include energy for regeneration and any periodic maintenance. Solar thermal energy usage can reduce these costs, but if electric heating is used, costs range from $0.05 to $0.15 per liter [17].

3) Larger Systems: Industrial-scale systems may involve investments up to $500,000 with operating costs between $0.04 and $0.10 per liter, depending on the energy source used for the regeneration process [21].

Environmental Impact: The environmental impact largely depends on the source of energy for desiccant regeneration. Using solar energy can substantially mitigate carbon emissions. Hanikel *et al.* (2019) demonstrated that the integration of solar thermal systems with desiccant-based AWG can reduce operating costs and environmental impact simultaneously [19].

Real-World Applications: These systems are particularly beneficial in remote and off-grid locations. In Sub-Saharan Africa, desiccation-based AWG units are deployed in rural communities, providing as much as 15 liters of potable water per day, with an initial setup cost of about $3500 and operating cost of around $0.07 per liter [20].

2.1.3. Comparative Analysis

When comparing condensation and desiccation-based AWG methods, several factors, including climatic conditions, energy consumption, scalability, water quality, and economic feasibility, are considered.

Energy Consumption:

1) Condensation-based systems generally consume more energy, approximately 0.2 kWh per liter of water [16].

2) Desiccation-based systems, particularly with solar thermal regeneration, may consume less energy under optimal conditions, reducing overall costs and environmental impacts [19].

Scalability:

1) Small-scale AWG units for personal or household use are widely available and affordable.

2) Scaling up to provide water for larger communities presents technical and economic challenges but shows promise with ongoing R&D efforts.

Water Quality: both methods typically produce high-quality water but require additional filtration and treatment to meet potable standards.

Maintenance costs for these systems include filters and other operational overheads, ranging from $100 to $500 annually [18].

Economic Feasibility:

1) Initial investments for small-scale systems range from $1000 to $5000.

2) Operating costs vary significantly based on energy consumption and source, ranging from $0.03 to $0.15 per liter.

3) Government incentives and subsidies, especially for systems integrating renewable energy, can make these technologies more accessible and affordable (Ford & Creel, 2018) [17].

2.1.4. Future Directions

Future research and development are focusing on enhancing the efficiency, reducing energy consumption, and expanding the scalability of AWG systems.

Materials Science: Advancements in MOFs and other highly efficient desiccants are improving the performance of desiccation-based systems [22].

Renewable Integration: Integration with renewable energy sources, particularly solar and wind, is critical for reducing operational costs and environmental footprint. Ford and Creel (2018) indicate that such integrations can cut operating costs by up to 50% [17].

Smart Technologies: The incorporation of IoT and smart control systems can optimize these devices' performance, making them more adaptive to varying environmental conditions and user demands.

Collaborative Efforts: Combined efforts from governments, private sectors, and research institutions are essential to drive innovation and ensure sustainable implementation. Policies providing subsidies and tax incentives can significantly impact the adoption and affordability of AWG technologies.

By innovatively addressing the challenges associated with water scarcity, AWG systems, whether condensation or desiccation-based, present viable and sustainable solutions for ensuring water security in arid regions.

2.2. Traditional and Advanced Desalination Techniques

Desalination has long been recognized as a critical technology for supplying fresh water, particularly in arid regions where natural freshwater resources are scarce. Traditional desalination methods primarily focus on reverse osmosis (RO) and thermal distillation, while advanced techniques are being developed to enhance efficiency and sustainability. This subchapter delves into these methods, evaluating their feasibility, efficiency, and financial implications, along with their environmental impacts.

2.2.1. Traditional Desalination Techniques

A) Reverse Osmosis (RO)

Reverse Osmosis is the most prevalent desalination technology globally. It operates by forcing seawater through a semi-permeable membrane that removes salts and impurities, producing potable water.

Feasibility and efficiency: RO systems are effective and widely used due to their relatively high recovery rate (typically 50% - 60%). The technology has evolved significantly, with modern membranes capable of rejecting more than 99% of dissolved salts [23].

Financial Data:

1) Capital costs: initial capital investments for RO desalination plants vary between $1000 and $2000 per cubic meter/day of capacity, reflecting extensive infrastructure and equipment costs. For instance, a plant with a capacity of 10,000 cubic meters per day would cost approximately $10 - 20 million [17].

2) Operating costs: the operational costs for RO desalination are primarily driven by energy consumption, maintenance, and membrane replacement. The energy usage is around 3 - 4 kWh per cubic meter of produced water. At an electricity rate of $0.12 per kWh, energy costs amount to $0.36 - $0.48 per cubic meter. Including maintenance and membrane replacement, the total operating cost ranges from $0.50 to $1.00 per cubic meter [24].

3) Environmental impact: the primary environmental concern with RO desalination is the brine discharge, which is concentrated saline waste with potential to harm marine ecosystems. Energy consumption also contributes to greenhouse gas emissions unless renewable energy sources are utilized. Advances in brine management and renewable energy integration are crucial to mitigating these impacts [25].

4) Real-World Applications: Large-scale RO desalination plants are operational worldwide, including the Ashkelon plant in Israel and the Carlsbad plant in California, each producing hundreds of millions of liters of fresh water daily [26].

B) Thermal Distillation

Thermal distillation, including Multi-Stage Flash (MSF) and Multiple Effect Distillation (MED), uses heat to evaporate seawater, which is then condensed to produce fresh water.

Feasibility and Efficiency: Thermal distillation is highly effective in removing salts and impurities, with recovery rates up to 90%. However, it requires significant energy input, primarily in the form of heat, making it less energy-efficient compared to RO [27].

Financial Data:

1) Capital Costs: Initial investment for thermal distillation plants is higher than RO, generally between $2000 and $4000 per cubic meter per day of installed capacity. A 10,000 cubic meters per day plant would cost roughly $20 - 40 million [28].

2) Operating Costs: Operating costs include the energy required for heating, maintenance, and scale prevention. Energy consumption is around 15 - 25 kWh per cubic meter. At an electricity rate of $0.12 per kWh, energy costs alone are $1.80 - $3.00 per cubic meter. Total operating costs range from $2.00 to $5.00 per cubic meter, depending on energy and operational efficiencies [29].

3) Environmental Impact: Like RO, thermal distillation produces brine, which must be managed to prevent ecological damage. The high energy requirement also poses sustainability concerns, which can be mitigated by integrating renewable energy sources such as solar thermal or waste heat recovery systems [30].

4) Real-World Applications: Thermal distillation is widely used in regions with abundant energy resources, such as the Middle East. Examples include the Shuaiba complex in Saudi Arabia and the Jebel Ali desalination plant in Dubai, both of which have capacities exceeding 100 million gallons per day [31].

2.2.2. Advanced Desalination Techniques

A) Forward Osmosis (FO)

Forward Osmosis uses a semi-permeable membrane and a draw solution with high osmotic pressure to extract water from seawater. The diluted draw solution is then separated to yield fresh water.

Feasibility and Efficiency: FO systems have the potential for lower energy consumption compared to RO, as they operate under lower pressure. However, challenges remain in finding efficient draw solutions and post-treatment methods [32].

Financial Data:

1) Capital costs: initial costs for FO plants are relatively lower, around $1000 to $1500 per cubic meter per day of capacity. A mid-sized plant producing 10,000 cubic meters per day may cost $10 - 15 million [32].

2) Operating costs: operating costs are still under extensive research but are estimated to be around $0.70 to $1.20 per cubic meter, primarily influenced by draw solution recovery and energy consumption [33].

3) Environmental impact: FO has lower energy consumption and reduced brine production compared to RO and thermal distillation, presenting fewer environmental concerns. However, the impact of the draw solutions used must be considered [34].

4) Real-world applications: FO is still emerging with pilot projects in operation, including one in Oman trialing the technology for brackish water resources

[35].

B) Capacitive Deionization (CDI)

Capacitive Deionization is an electrochemical method that removes ions from water using electric fields. It is particularly effective for brackish water desalination.

Feasibility and Efficiency: CDI is efficient for low-salinity water sources, consuming less energy than traditional desalination methods. It has a recovery rate of around 70% - 80% for brackish water [36].

Financial Data:

1) Capital costs: initial investment for CDI systems ranges from $800 to $1200 per cubic meter per day of capacity. Thus, a plant with a daily capacity of 10,000 cubic meters may cost about $8 - 12 million [37].

2) Operating costs: operating costs are lower relative to RO, estimated at $0.30 to $0.60 per cubic meter, largely due to lower energy consumption (1.0 - 1.5 kWh per cubic meter) and minimal maintenance requirements [38].

3) Environmental impact: CDI produces minimal brine waste and requires significantly less energy compared to RO and thermal distillation, making it environmentally friendly. However, the disposal of electrodes at the end of their life cycle presents a minor environmental concern [39].

4) Real-World Applications: CDI is currently used in smaller-scale applications but is expanding. For instance, the Netherlands employs CDI for water softening and agricultural irrigation [40].

C) Membrane Distillation (MD)

Membrane Distillation involves passing warm saline water through a hydrophobic membrane. The water vapor passes through the membrane, leaving salts behind, and condenses on the cooler side to produce fresh water.

Feasibility and Efficiency: MD can operate at lower temperatures than traditional thermal processes, making it compatible with solar thermal and waste heat. The recovery rate is generally high, around 90% - 95%, but the technology is still developing to address membrane fouling issues and efficiency [41].

Financial Data:

1) Capital Costs: Current estimates suggest initial investments from $1500 to $2500 per cubic meter per day of capacity. A 10,000 cubic meters per day plant could hence cost around $15 - 25 million [42].

2) Operating Costs: Operating costs, influenced by energy (1 - 2 kWh per cubic meter from low-grade heat sources) and membrane maintenance, are estimated at $0.80 to $1.50 per cubic meter [43].

3) Environmental Impact: Utilizing low-grade and renewable energy sources significantly reduces the environmental impact. Moreover, MD produces less concentrated brine, thereby mitigating marine discharge issues [44].

4) Real-World Applications: MD is used in small-scale applications, but pilot plants are being developed for larger-scale use. For example, a pilot plant in Spain uses solar thermal energy to drive MD processes for desalination [45].

2.2.3. Comparative Analysis

A) Energy Consumption:

Traditional methods (RO and thermal distillation) are energy-intensive, with RO being more energy-efficient. Advanced methods like FO, CDI, and MD offer significantly lower energy consumption, enhancing sustainability [46].

B) Scalability:

Traditional systems (RO and thermal distillation) are well-established and scalable.

Advanced methods are in various stages of development with promising potential for scalability [47].

C) Economic Viability:

Traditional methods: RO has become more cost-effective over the years, while thermal distillation remains costlier.

Advanced methods: CDI and FO currently offer favorable cost profiles, with MD presenting potential for cost reductions with further technological advancements [48].

D) Environmental Impact:

Both traditional and advanced methods need to address brine management. Advanced methods present enhanced sustainability by leveraging low energy consumption and reduced environmental footprints [49].

E) Future Directions:

Future R&D focuses on improving the efficiency and reducing the costs of advanced desalination technologies. Innovations in materials science, energy sources, and smart technologies hold promise for the future of desalination, ensuring sustainable solutions for addressing water scarcity [42].

By understanding the financial, environmental, and operational aspects of both traditional and advanced desalination techniques, stakeholders can make informed decisions to ensure the long-term sustainability of water resources, particularly in water-scarce arid regions.

2.3. Water Recycling and Reuse

Water recycling and reuse are crucial strategies in addressing water scarcity, especially in arid regions where natural fresh water supplies are limited. By treating and reusing wastewater, communities can significantly reduce their dependence on traditional water sources, minimize environmental degradation, and promote sustainable water management practices. This subchapter explores the feasibility, efficiency, environmental impact, and financial implications of various water recycling and reuse technologies.

2.3.1. Overview of Water Recycling and Reuse

Water recycling involves the process of treating wastewater to remove contaminants and producing water that is safe for various uses. Reuse, on the other hand, refers to the beneficial application of treated water in agricultural, industrial, and even potable contexts. Through these processes, water demand can be reduced, enhancing resilience against water scarcity.

Types of Water Recycling and Reuse:

1) Greywater Recycling: Greywater is wastewater from baths, sinks, and washing machines, which can be treated and reused for irrigation, toilet flushing, and landscape watering. Greywater recycling systems are relatively simple and cost-effective, making them ideal for residential applications.

2) Blackwater Recycling: Blackwater recycling involves treating sewage water, which contains human waste. Advanced treatment processes are required to ensure the water meets safety standards for reuse, often in industrial and agricultural settings.

3) Industrial Water Reuse: Industries can treat and reuse their wastewater in various processes, reducing the need for fresh water and lowering operational costs.

4) Agricultural Water Reuse: Treated wastewater can be used in agriculture for irrigation, thus conserving fresh water and enhancing crop yield.

5) Indirect Potable Reuse: Treated wastewater is discharged into natural water bodies (lakes, rivers, or aquifers), where it blends with other water sources before being extracted and further treated for potable use.

2.3.2. Technologies for Water Recycling and Reuse

A) Membrane Bioreactor (MBR) Systems

Membrane bioreactor (MBR) systems combine biological treatment processes with membrane filtration to produce high-quality reclaimed water. MBR systems are effective in removing organic matter, bacteria, and viruses from wastewater.

Feasibility and Efficiency: MBR systems are highly efficient, with removal rates for contaminants often exceeding 95%. They are suitable for high-strength wastewaters and can be used in both municipal and industrial applications [50].

Financial Data:

1. Capital Costs: The initial capital cost for MBR systems ranges from \$1000 to \$3000 per cubic meter per day of treatment capacity. A plant with a daily capacity of 5000 cubic meters may cost \$5 - 15 million [51].

2) Operating Costs: Operating costs, including energy, maintenance, and membrane replacement, typically range from \$0.50 to \$1.00 per cubic meter. Energy consumption is around 1 - 2 kWh per cubic meter [52].

3) Return on Investment: MBR systems can offer substantial savings in water costs for industries, with a payback period ranging from 5 to 10 years depending on the scale and specific application [53].

Environmental Impact: MBR systems produce high-quality effluent suitable for various reuse applications, reducing the load on natural water bodies and minimizing environmental contamination. The sludge produced can be further processed for energy recovery or used as fertilizer, enhancing sustainability [54].

Real-World Applications: Cities like Singapore and Tokyo use MBR technology for large-scale water recycling projects, producing millions of liters of reclaimed water daily [54].

B) Reverse Osmosis (RO) for Water Recycling

Reverse Osmosis (RO) systems are extensively used for recycling wastewater, especially in industrial and potable reuse applications. RO membranes effectively remove dissolved salts, organics, and pathogens from treated wastewater.

Feasibility and Efficiency: RO can achieve removal efficiencies above 99%. It is suitable for high-salinity wastes and applications requiring high water purity [55].

Financial Data:

1) Capital costs: RO systems for water recycling have capital costs ranging from \$1500 to \$5000 per cubic meter per day of capacity. For a plant treating 10,000 cubic meters per day, costs may reach \$15 - 50 million [56].

2) Operating costs: operating costs, largely driven by energy consumption (3 - 6 kWh per cubic meter), chemicals, and membrane maintenance, range from \$0.60 to \$1.50 per cubic meter [57].

3) Economic viability: wastewater RO can significantly lower industrial water costs, with payback periods of 3 - 7 years, especially when integrated with renewable energy sources [57].

4) Environmental impact: like any RO process, brine management is critical to mitigate environmental impacts. Innovations in brine concentration and disposal techniques are enhancing the sustainability of RO-based recycling systems [58].

5) Real-World Applications: California's Groundwater Replenishment System (GWRS) utilizes RO to treat wastewater, producing potable water for over 850,000 residents [59].

C) Constructed Wetlands

Constructed wetlands are engineered systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to treat wastewater.

Feasibility and Efficiency: Constructed wetlands can effectively remove nutrients, suspended solids, heavy metals, and pathogens. They are particularly suited for decentralized, small-to-medium scale water recycling applications [60].

Financial Data:

Capital costs: initial capital costs for constructed wetlands are relatively low, at approximately \$500 to \$1500 per cubic meter per day of capacity. Small systems for communities or industries may cost \$250,000 to \$1.5 million [12].

Operating costs: operating costs are minimal, often below \$0.20 per cubic meter, primarily for vegetation management and occasional dredging [61].

Return on Investment: while the financial return depends on specific applications, constructed wetlands offer significant savings by reducing the need for chemical water treatment and providing ecosystem services such as habitat creation [62].

Environmental impact: constructed wetlands provide multiple ecological benefits, including biodiversity enhancement, carbon sequestration, and water polishing, making them highly sustainable [63].

Real-world applications: countries like China and Denmark have implemented extensive constructed wetland systems for wastewater treatment in rural areas, significantly improving local water quality [64].

2.3.3. Financial Analysis of Water Recycling Programs

Incentives and Funding: Governments often provide incentives such as grants, tax credits, and low-interest loans to promote water recycling. For instance, the US Environmental Protection Agency (EPA) offers funding for water recycling projects through its State Revolving Fund (SRF) program [65].

Cost-Benefit Analysis: Water recycling can be cost-effective in the long term. For example, the Orange County Water District in California reports recycled water costs of approximately $850 per acre-foot, compared to $1200 per acre-foot for imported water [66].

Decentralized Systems Cost Efficiency: Decentralized recycling systems (e.g., for individual buildings or small communities) can also be economically viable. The capital costs for greywater systems in residential buildings range from $1000 to $3000, with operating costs of around $100 to $200 annually [67].

2.3.4. Challenges and Future Directions

The template Technical Challenges: Water recycling systems must ensure contaminant removal to meet stringent regulatory standards for different reuse purposes. Addressing issues like membrane fouling in RO systems and optimizing biological processes in MBR and constructed wetlands are ongoing research areas [68].

Public Perception and Acceptance: Public acceptance of recycled water, especially for potable use, remains a challenge. Education and communication strategies are essential to overcoming the “yuck factor” associated with recycled water [69].

Policy and Regulation: Robust regulatory frameworks must support water recycling initiatives, ensuring water quality and safety. Policies should also promote the integration of recycled water into broader water management strategies [70].

Innovation and research: advanced treatment technologies, such as hyper-filtration membranes, bio-electrochemical systems, and hybrid treatment processes, are under development to enhance efficiency and cost-effectiveness [15].

Collaboration: multidisciplinary collaborations involving government agencies, private sector, academia, and communities are critical to advance water recycling and ensure sustainable implementation [71].

Water recycling and reuse present viable and sustainable solutions to water scarcity. With advancements in treatment technologies, supportive policies, and increased public acceptance, these practices can significantly enhance water security, particularly in arid regions.

2.4. Feasibility and Performance of Current Methods

The feasibility and performance of water production methods are critical aspects that determine their suitability for large-scale implementation in arid regions. This subchapter evaluates atmospheric water generation, desalination, and water recycling, focusing on their technical feasibility, operational performance, economic viability, and environmental impact.

2.4.1. Atmospheric Water Generation (AWG)

Technical Feasibility: Atmospheric water generation (AWG) is technically feasible using either condensation-based or desiccation-based systems. Condensation-based AWG, which cools air to collect condensed water, is effective in areas with higher humidity. Desiccation-based AWG utilizes desiccants to absorb moisture, making it suitable for drier climates [16].

Operational Performance: Modern AWG systems are reasonably efficient, with condensation-based methods typically yielding 0.2 to 5 liters of water per kWh, depending on ambient humidity and temperature conditions. Desiccation methods, especially those employing advanced materials like Metal-Organic Frameworks (MOFs), also promise efficient water capture but require reliable and sustainable energy sources for the regeneration process [18].

Economic Viability:

Capital Costs: Small-scale AWG units range from $1000 to $5000, while larger commercial systems can cost between $10,000 and $500,000, depending on capacity and technology [18].

Operating Costs: Operating costs for AWG systems depend heavily on energy consumption. Condensation-based systems incur significant electrical costs (0.2 - 0.5 kWh/L), while desiccation systems can reduce costs with solar thermal integration. Overall, operating expenses range from $0.05 to $0.15 per liter produced, varying by locale and energy source [19].

Environmental Impact: The environmental impact of AWG depends on energy sources. AWG systems powered by renewable energy (solar or wind) can significantly lower carbon footprints. However, systems relying on fossil fuels may contribute to greenhouse gas emissions, thus diminishing environmental benefits [22].

2.4.2. Desalination Technologies

Technical Feasibility: Desalination technologies, particularly Reverse Osmosis (RO) and thermal distillation, are well-established methods for producing fresh water from seawater or brackish water. RO is widely adopted due to its effectiveness and relatively lower energy requirements, whereas thermal distillation, including Multi-Stage Flash (MSF) and Multiple Effect Distillation (MED), is suited for waters with high salinity [27].

Operational Performance:

RO Systems: modern RO membranes exhibit high salt rejection rates (>99%) and are capable of processing large volumes of water. The specific energy consumption for RO systems has decreased to around 3 - 4 kWh per cubic meter, thanks to technological advancements [55].

Thermal distillation: MSF and MED systems are efficient in removing dissolved salts and impurities, with recovery rates up to 90%. However, they remain energy-intensive, requiring approximately 15 - 25 kWh per cubic meter of water produced [29].

Economic Viability:

Capital costs: RO plants cost between $1000 and $2000 per cubic meter per day of capacity, translating to $10 - 20 million for a 10,000 cubic meter/day plant. Thermal distillation plants have higher capital costs, ranging from $2000 to $4000 per cubic meter per day [72].

Operating costs: RO operational costs range from $0.50 to $1.00 per cubic meter, while thermal distillation costs range from $2.00 to $5.00 per cubic meter, influenced by energy prices and operational efficiencies [42].

Environmental Impact: Key environmental issues for desalination include brine disposal and energy use. Innovations in brine management and renewable energy utilization are critical for enhancing the sustainability of desalination operations [73].

2.4.3. Water Recycling and Reuse

The template Technical Feasibility: Water recycling technologies, such as Membrane Bioreactor (MBR) systems, constructed wetlands, and Reverse Osmosis (RO) for wastewater, are increasingly used to treat and repurpose wastewater for various applications, including industrial processes, agriculture, and potable reuse [51].

Operational Performance:

MBR Systems: MBR systems combine biological treatment and membrane filtration, achieving high contaminant removal (>95%). These systems are widely used for municipal and industrial wastewater treatment [74] [75].

Constructed wetlands: these systems harness natural processes, providing effective nutrient removal and water polishing with relatively low operational costs [60].

RO for recycling: RO is effective in treating and recycling wastewater, producing high-quality water that meets stringent reuse standards, with removal efficiencies exceeding 99% [55].

Economic Viability:

Capital Costs:

MBR systems: $1000 to $3000 per cubic meter per day capacity [60].

Constructed wetlands: $500 to $1500 per cubic meter per day capacity [55].

RO for wastewater recycling: $1500 to $5000 per cubic meter per day capacity [56].

Operating Costs:

MBR systems: $0.50 to $1.00 per cubic meter [74].

Constructed wetlands: <$0.20 per cubic meter [60].

RO for recycling: \$0.60 to \$1.50 per cubic meter [55].

Environmental Impact: Water recycling significantly reduces the demand on freshwater resources and lowers wastewater discharge into natural water bodies. However, energy consumption and the lifecycle impact of treatment chemicals must be managed to ensure sustainability [15].

2.4.4. Comparative Analysis and Future Directions

In assessing the feasibility and performance of atmospheric water generation (AWG), desalination, and water recycling, several critical factors emerge.

A) Energy Consumption

Both AWG and desalination technologies, particularly thermal distillation, are typically energy-intensive. For example, AWG using condensation methods can consume 0.2 to 0.5 kWh/L, while thermal distillation may require 15 - 25 kWh per cubic meter [16] [29]. The integration of renewable energy sources, such as solar and wind, is paramount to reducing operational costs and minimizing environmental impacts. Water recycling technologies, such as constructed wetlands and membrane bioreactors (MBRs), offer lower energy footprints, enhancing their sustainability. MBR systems typically consume 1 - 2 kWh per cubic meter, and constructed wetlands operate with minimal energy input [50] [60].

B) Scalability

Desalination technologies are well-suited for large-scale applications, with existing infrastructure supporting municipal-scale water supply. For instance, the Carlsbad Desalination Plant supplies 50 million gallons of fresh water daily to San Diego County [26]. In contrast, AWG systems are more adaptable for decentralized use, serving communities, remote areas, and individual households effectively. For example, small-scale AWG units can produce up to 10 liters daily per household [76]. Water recycling is versatile, supporting both centralized treatments, such as municipal wastewater recycling, and decentralized applications like residential greywater systems.

C) Economic Viability

Water recycling generally exhibits the lowest operating costs among the methods studied. For instance, MBR systems and constructed wetlands can operate at \$0.50 to \$1.00 and <\$0.20 per cubic meter, respectively [5] [51]. In comparison, AWG and desalination, particularly Reverse Osmosis (RO), tend to have higher costs. Operating costs for RO desalination and AWG range from \$0.50 to \$1.50 and \$0.05 to \$0.15 per liter, respectively [17] [42]. The cost-effectiveness of these technologies is highly contingent on local conditions, energy prices, and regulatory frameworks. Financial incentives and subsidies can further enhance economic feasibility. For instance, subsidies for solar-powered AWG systems can significantly reduce both capital and operating costs, promoting wider adoption [67].

D) Environmental Impact

Environmental considerations include the by-products of each method. Desalination produces brine, which necessitates careful management to prevent marine ecosystem damage. AWG's environmental impact largely hinges on the energy source, with renewable-powered systems presenting less impact compared to those using fossil fuels [73]. Water recycling, particularly using constructed wetlands, offers substantial environmental benefits by reducing freshwater extraction and promoting ecosystem services.

E) Future Directions

Advancements in materials science, energy efficiency, and smart water management technologies are critical for enhancing the performance and feasibility of these water production methods. Photovoltaic and thermal-powered desalination, along with next-generation MOFs for AWG, represent promising areas of research [15]. Additionally, smart management systems integrating the Internet of Things (IoT) could optimize operational efficiencies and adaptability to variable environmental conditions.

Policy support and collaborative efforts among governments, private entities, and research institutions will be instrumental in driving the sustainable implementation of these strategies. Policymakers can facilitate the adoption of advanced water production technologies through targeted subsidies, grants for R&D, and regulatory frameworks supporting sustainable practices [76].

Evaluating these technical, economic, and environmental dimensions empowers stakeholders to select the most appropriate and sustainable water production methods for specific needs, ensuring long-term water security and resilience in arid regions.

3. Innovative Water Collection Techniques

This chapter focuses on emerging water collection methods such as fog nets, dew harvesting, and solar still evaporation techniques. It examines the principles, mechanisms, and potential applications of these innovative techniques, highlighting their benefits and challenges for large-scale deployment in arid regions.

Innovative water collection methods are gaining attention as viable solutions to address water scarcity, particularly in arid and semi-arid regions. This chapter delves into emerging techniques such as fog nets, dew harvesting, and solar still evaporation. Each method is examined in terms of the principles they are based on, the mechanisms employed, and their potential applications. The analysis will also consider the benefits and challenges associated with their large-scale deployment.

Fog Nets and Dew Harvesting

A) Principles and Mechanisms

1) Fog Nets: Fog nets are designed to capture water droplets from fog using mesh fabrics that intercept and condense the moisture. The principle behind fog collection leverages the high moisture content in fog, even in arid regions, as fog

can contain up to 0.5 grams of water per cubic meter. Mesh materials, often made from polyethylene or polypropylene, are suspended vertically to intercept dew-laden winds. As the air flows through the mesh, water droplets form and cling to the fibers, eventually coalescing and trickling down into collection troughs at the base [77].

2) Dew Harvesting: Dew harvesting exploits nocturnal temperature drops that cause water vapor in the air to condense on surfaces. The process is driven by radiative cooling, where surfaces release heat and cool down below the dew point temperature, allowing dew to form. Dew harvesters are typically designed with inclined surfaces made of materials with high thermal conductivity to facilitate efficient condensation [78].

B) Applications and Benefits

Fog Nets: Fog nets are particularly effective in coastal and mountainous regions where fog is prevalent. Projects in Chile, Peru, and Morocco have demonstrated the effectiveness of fog nets in capturing significant amounts of water. For example, the fog collection project in the Atacama Desert of Chile, one of the driest places on earth, has successfully provided up to 15 liters of water per square meter of net per day [29].

C) Financial Data:

a) Capital costs: the initial setup cost for fog nets ranges from $10 to $30 per square meter of mesh. Thus, a medium-sized installation covering 1000 square meters might cost between $10,000 and $30,000 [78].

b) Operating costs: initial setup costs for fog nets range from $10 to $30 per square meter, with minimal maintenance costs estimated at $200 to $400 annually for a 1000 square meter installation [29].

c) Environmental Impact and Challenges: Fog nets have a low environmental impact, as they do not alter the atmospheric water cycle or require significant energy inputs. However, challenges include potential damage from strong winds and clogging of the mesh with dust and debris. Regular maintenance is essential for optimal performance.

Dew Harvesting: Dew harvesting is suitable for regions where diurnal temperature variations lead to significant nighttime cooling. Applications include agricultural irrigation, drinking water supply in remote areas, and supplementary water sources for residential use. Research in India has shown that optimized dew harvesting systems can collect up to 0.8 liters of water per square meter of collection surface per night [78].

D) Real-World Implementations and Case Studies

1) Fog Nets: The Tojquia community in Guatemala benefits from installing fog nets, producing approximately 4000 liters of clean water daily. This project not only reduced water scarcity but also improved local health and agricultural productivity. Similarly, the El Tofo project in Chile has become a model for large-scale fog collection, demonstrating potential applicability in other fog-rich areas globally [29].

2) Dew Harvesting: In Kutch, India, dew harvesting systems have provided a reliable water source for rural communities, significantly reducing dependence on erratic rainwater and groundwater supplies [78]. The pilot projects in Sde Boqer, Israel, and Agadir, Morocco, have further validated the feasibility and effectiveness of these systems in arid climates [79].

E) Comparative Analysis and Future Directions

When comparing fog nets and dew harvesting, several factors stand out:

a) Energy Consumption: Both methods are highly energy-efficient, requiring minimal to no external energy input. This feature is particularly beneficial for remote or off-grid communities.

b) Scalability: Fog nets are scalable, especially in regions with consistent fog. Similarly, dew harvesting can be scaled up where significant night-day temperature variations occur regularly.

c) Economic Viability: Both methods involve relatively low initial investments and operating costs, making them economically feasible for both small and large-scale applications. Financial viability is further enhanced by minimal maintenance requirements and low operational costs.

d) Environmental Impact: Both fog nets and dew harvesting are highly energy-efficient, relying on natural processes with low environmental footprints, making them suitable for remote and off-grid communities [79].

e) Future Directions: Further research should focus on improving the efficiency and durability of fog net materials and optimizing the surfaces used for dew harvesting. Innovations in material science could lead to more efficient water collection surfaces, increasing yield and reliability. Policy support and community engagement will be crucial for the successful implementation and sustained operation of these technologies [79].

By evaluating these technological, economic, and environmental dimensions, stakeholders can choose the most suitable and sustainable water collection methods, ensuring long-term water security in arid regions.

4. New Physical Methods for Fresh Water Production

This chapter introduces cutting-edge physical methods for water production, encompassing advanced atmospheric water harvesting, geothermal water extraction, piezoelectric moisture harvesting systems, and innovative membrane technologies in desalination. Each method’s potential for scalability, efficiency, and sustainability is analyzed [13].

4.1. Advanced Atmospheric Water Harvesting

Advanced atmospheric water harvesting (AWH) technologies are gaining traction as viable solutions to mitigate water scarcity in arid and semi-arid regions. These technologies leverage the moisture present in the air, even in low-humidity environments, to produce fresh water. This section delves into the materials and nanotechnology applications, as well as the integration with renewable energy sources, to evaluate the potential of AWH systems.

4.1.1. Materials and Nanotechnology Applications

The efficacy of AWH systems largely depends on the materials used for capturing and condensing water vapor. Recent advancements in materials science and nanotechnology have significantly enhanced the performance of these systems.

a) Metal-Organic Frameworks (MOFs): Metal-Organic Frameworks (MOFs) are a class of materials known for their high surface area and tunable porosity, making them ideal for capturing water vapor from the air. MOFs like MOF-801, MOF-841, and MOF-303 have shown exceptional performance in water harvesting applications [80] [81].

MOF-801: Research indicates that MOF-801 can capture up to 0.25 grams of water per gram of material per cycle in low humidity environments (20% - 30% relative humidity). Its high water affinity and robust thermal stability make it suitable for diverse climatic conditions [81].

MOF-841 and MOF-303: These MOFs exhibit even higher water uptake capacities, with MOF-841 capturing about 0.4 grams per gram and MOF-303 up to 0.6 grams per gram under similar conditions. Their unique structures enable efficient adsorption and release of water molecules, enhancing the overall efficiency of AWH systems [82] [83].

b) Advanced Polymers and Hydrogels: polymers and hydrogels are other promising materials for AWH. They can absorb substantial amounts of water due to their hydrophilic nature and expansive surface areas.

Hydrogels: these materials can absorb water up to several hundred times their weight. When integrated into AWH systems, hydrogels can facilitate continuous water harvesting cycles due to their rapid absorption and release characteristics [84].

Functionalized polymers: polymers functionalized with hygroscopic (water-attracting) groups have shown improved water capture efficiency. These materials can be engineered to exhibit selective water adsorption, enhancing the overall performance of AWH systems [83] [85].

Financial Data:

Capital costs: the initial investment for AWH systems using MOFs can range from \$1500 to \$3000 per cubic meter per day of capacity, depending on the specific MOF material and system configuration. For polymer-based systems, the costs are slightly lower, ranging from \$1200 to \$2500 per cubic meter per day [86] [87].

Operating costs: operating costs for AWH systems are relatively low, primarily involving energy for regeneration and periodic maintenance. For MOF-based systems, the operating costs range from \$0.20 to \$0.40 per liter, whereas polymer-based systems may cost slightly less, from \$0.15 to \$0.35 per liter [87].

4.1.2. Integration with Renewable Energy Sources

The integration of renewable energy sources with AWH systems is crucial for enhancing sustainability and reducing the environmental impact. Solar and wind energy are the primary renewable sources used to power AWH technologies.

a) Solar-powered AWH: Solar energy is widely used for regeneration processes in MOF and polymer-based AWH systems. Solar collectors and photovoltaic panels provide the necessary thermal and electrical energy to desorb captured water, making the process energy-efficient and eco-friendly.

Solar thermal regeneration: solar thermal collectors can generate high temperatures required for the regeneration of MOFs, enhancing their water release capacity. Studies have shown that solar thermal systems can achieve regeneration efficiencies of up to 90%, significantly reducing operational costs [88].

Photovoltaic (PV) systems: PV panels convert sunlight into electricity to power AWH units. The use of PV systems is especially advantageous in remote or off-grid regions, where conventional electricity sources are unavailable. The efficiency of PV systems has been steadily increasing, with current panels achieving efficiencies of over 20% [89].

b) Wind-powered AWH: wind energy is another renewable source that can be harnessed to power AWH systems. Wind turbines generate electricity that can be used for water capture and regeneration processes.

Wind turbines: the integration of small-scale wind turbines with AWH systems can provide a consistent power supply, particularly in regions with strong and steady winds. This integration enhances the sustainability of AWH operations, reducing reliance on non-renewable energy sources [89] [90].

Challenges and Future Directions:

Despite the promising advancements, several challenges remain in scaling up AWH technologies for widespread use. These include the high costs of advanced materials, energy requirements for regeneration, and the need for efficient system designs that can operate effectively in varying climatic conditions [91].

Future research should focus on:

1) Material innovations: recent advancements in MOFs, hydrogels, and functionalized polymers have significantly improved the performance of AWH systems, enabling higher water capture efficiencies at lower regeneration energy requirements" [84].

2) Hybrid systems: exploring hybrid AWH systems that combine multiple technologies (e.g., MOFs, hydrogels, functionalized polymers) to maximize water capture efficiency.

3) Cost reduction: scaling up production and optimizing manufacturing processes to reduce the costs of advanced materials and system components.

4) Integration with Renewable Energy: "Wind and solar energy integrations significantly reduce the operational costs and environmental impacts of AWH systems, enhancing their sustainability in diverse climatic conditions [22].

Real-World Applications:

Several pilot projects and real-world applications demonstrate the potential of advanced AWH technologies:

WaterGen's GENius: WaterGen's GENius technology uses an advanced air filtration system and heat exchanger to capture water vapor from the air. The system can produce up to 800 liters of water per day, powered by solar panels. This technology has been deployed in various regions, including disaster-stricken areas and rural communities [92].

MIT's MOF-Based AWH System: Researchers at MIT have developed an AWH system using MOFs that can operate effectively in low-humidity environments. The system was tested in the Mojave Desert, producing over 2.8 liters of water per kilogram of MOF per day [81].

Harvard's Hydrogel-Based AWH: Harvard University's hydrogel-based AWH system leverages the high water absorption capacity of hydrogels. The system has shown promising results in both laboratory and field tests, providing a sustainable water source in arid regions [93].

Financial Viability and Environmental Impact:

The financial viability of advanced AWH systems hinges on reducing capital and operating costs while enhancing water capture efficiency. The integration of renewable energy sources is critical for achieving this goal, as it reduces dependency on non-renewable energy and lowers operational costs.

Environmental Impact:

Positive Impacts: AWH systems have a low environmental footprint compared to traditional water extraction methods. They do not deplete natural water sources or require extensive infrastructure, making them suitable for remote or ecologically sensitive areas [94].

Challenges: The production and disposal of advanced materials like MOFs and polymers pose environmental challenges. Ensuring sustainable manufacturing processes and recycling or reusing materials will be essential to minimize environmental impact [91].

4.2. Geothermal Water Extraction

Geothermal water extraction leverages Earth's internal heat to produce water, combining geophysical techniques for water prospecting with thermal desalination.

4.2.1. Geophysical Techniques for Water Prospection

Geophysical Techniques for Water Prospection

Geophysical techniques are essential in identifying geothermal reservoirs, which are critical for geothermal water extraction.

Seismic Methods: These methods involve generating seismic waves and measuring their travel times through subsurface formations. Variations in wave velocity indicate the presence of geothermal reservoirs [95].

Magnetotelluric Surveys: This technique measures natural geomagnetic and geoelectric field variations to infer the electrical conductivity of subsurface materials, helping identify hot water and steam reservoirs [96].

Gravity and Magnetic Surveys: Variations in gravity and magnetic fields are used to map subsurface structures, revealing potential geothermal reservoirs

[97].

Financial Data:

Capital Costs: The costs for geophysical surveys can range from $150,000 to $500,000 depending on the survey's scope and depth [98].

Operational Costs: Ongoing costs for data analysis and continuous monitoring range from $20,000 to $100,000 annually [98].

4.2.2. Thermal Desalination Combined with Geothermal Sources

Harnessing geothermal energy for thermal desalination offers an efficient and sustainable method of water production.

Multi-Stage Flash (MSF) Desalination: Using high-temperature steam from geothermal sources, MSF involves flashing seawater multiple times to generate steam, which condenses as fresh water [47].

Multi-Effect Distillation (MED): MED employs multiple stages where seawater is evaporated and condensed sequentially using geothermal heat to produce fresh water [99].

Financial Data:

Capital Costs: For a 10,000 cubic meter per day geothermal desalination plant, costs range from $20 million to $40 million [100].

Operating Costs: Using geothermal energy, the operating costs can be reduced to $1.00 to $2.00 per cubic meter of water produced [100].

4.3. Piezoelectric Moisture Harvesting Systems

Piezoelectric moisture harvesting systems utilize piezoelectric materials that generate electric charges in response to mechanical stress (e.g., wind or raindrops), which can then be used to drive water extraction processes.

Principles: Piezoelectric materials like PZT (lead zirconate titanate) generate electricity when mechanically deformed. This electricity can be harnessed to power small-scale water condensation units where the mechanical energy from environmental factors like wind or raindrops is converted to electrical energy, driving the condensation process [101].

Applications: These systems are suitable for micro-scale water harvesting applications, particularly in remote or off-grid locations where conventional power sources are unavailable.

Financial Data:

Capital Costs: Initial setup costs for piezoelectric systems range from $1000 to $3000 per unit, depending on the system's capacity and design [102].

Operating Costs: These systems have minimal operating costs, primarily maintenance-related, estimated at $50 to $100 annually [103].

4.4. Innovative Membrane Technologies in Desalination

Innovative membrane technologies represent the forefront of desalination advancements, focusing on enhancing efficiency and reducing energy consumption.

Graphene Oxide Membranes: Graphene oxide membranes are known for their high permeability and selectivity, capable of filtering salts and other impurities from water efficiently. These membranes are particularly significant in reverse osmosis (RO) applications [104].

Aquaporin-Based Membranes: Mimicking biological water channels in human cells, aquaporin-based membranes offer high water permeability and salt rejection rates. Their biomimetic properties make them ideal for desalination processes, promising reduced energy consumption and enhanced performance [105].

Financial Data:

Capital Costs: Costs for implementing innovative membrane technologies in desalination systems range from $2000 to $5000 per cubic meter per day capacity [106].

Operating Costs: Operating costs for these systems typically range from $0.50 to $1.20 per cubic meter, primarily driven by energy consumption and membrane maintenance [13].

By integrating these advanced techniques and materials, the efficiency, scalability, and sustainability of water production methods can be significantly enhanced. Continued research and innovation are essential for overcoming existing challenges and maximizing the potential of these groundbreaking technologies.

5. Technological Feasibility and Economic Considerations

This chapter examines the economic and technical feasibility of implementing advanced water production technologies such as atmospheric water harvesting, geothermal water extraction, piezoelectric moisture harvesting, and innovative membrane desalination. It includes analyses of required investments, cost-benefit ratios, potential funding sources, and risk management strategies. The goal is to provide a realistic assessment of how these technologies can be effectively implemented in arid regions [100].

5.1. Required Investments and Economic Viability

The upfront capital investment and ongoing operational costs are crucial considerations for the economic viability of advanced water production technologies.

A) Atmospheric water harvesting (AWH): the capital costs for MOF-based AWH systems range from $1500 to $3000 per cubic meter per day of capacity. For polymer-based systems, costs are slightly lower, ranging from $1200 to $2500 per cubic meter per day [80]. These costs include materials, installation, and initial setup.

Operating costs: MOF-based AWH systems have operating costs ranging from $0.20 to $0.40 per liter, while polymer-based systems range from $0.15 to $0.35 per liter. These costs cover energy for regeneration, periodic maintenance, and replacement of materials [81].

B) Geothermal water extraction: geothermal desalination plants require significant initial investment due to the need for geophysical surveys, drilling, infrastructure, and desalination units.

Capital costs: the costs for establishing a geothermal desalination plant of 10,000 cubic meters per day capacity range from $20 million to $40 million [107]. This includes costs for seismic surveys, drilling, plant construction, and installation of thermal desalination units [108].

Operating costs: using geothermal energy, operating costs can be reduced to $1.00 to $2.00 per cubic meter of produced water. These costs account for regular maintenance, energy consumption, and labor [99].

C) Piezoelectric moisture harvesting systems: piezoelectric systems are particularly effective for micro-scale water harvesting, suitable for remote or off-grid locations.

Capital costs: setup costs for piezoelectric systems range from $1000 to $3000 per unit, depending on capacity and design. These costs encompass the cost of piezoelectric materials, installation, and initial setup [109].

Operating costs: operating costs are minimal, primarily intended for periodic maintenance, roughly estimated at $50 to $100 annually [102].

D) Innovative membrane technologies in desalination: advancements in membrane desalination, such as graphene oxide and aquaporin-based membranes, improve efficiency and reduce energy consumption.

Capital costs: implementing innovative membrane technologies in desalination systems range from $2000 to $5000 per cubic meter per day capacity. These costs cover membrane materials, installation, and initial setup of desalination units [104].

Operating costs: operating costs for these systems typically range from $0.50 to $1.20 per cubic meter, primarily driven by energy consumption and membrane maintenance. The longer lifespan and reduced fouling rates of these advanced membranes contribute to lower operational costs [105].

Financial viability: comprehensive financial models should assess not only the upfront capital costs and ongoing operational expenses but also the potential savings and benefits derived from using advanced water production technologies. Factors such as reduced reliance on imported water, lower environmental impact, and increased water security must be considered. Financial incentives, such as subsidies, tax credits, and low-interest loans, can enhance the economic viability of these technologies.

5.2. Timeframe for Large-Scale Implementation

Implementing advanced water production technologies on a large scale involve several phases, including research and development, pilot testing, scaling up, and full-scale deployment.

A) Research and development (R&D): the R&D phase involves laboratory testing, material optimization, and initial field trials. This phase can last from 1 to 3 years, depending on the complexity of the technology and the extent of required innovations [13].

B) Pilot testing: pilot projects are designed to validate the performance and feasibility of the technologies in real-world conditions. Pilot testing typically lasts 1 to 2 years, during which data on efficiency, reliability, and environmental impact are collected and analyzed [80].

C) Scaling up: scaling up involves expanding the pilot systems to larger capacities suitable for community or municipal use. This phase includes securing funding, obtaining regulatory approvals, and establishing necessary infrastructure. Scaling up can take 2 to 5 years, depending on the size and scope of the project [81].

D) Full-Scale deployment: full-scale deployment involves widespread implementation of the technology to serve the intended population. This phase involves comprehensive logistics planning, mass production of materials, construction of facilities, and operational ramp-up. Full-scale deployment can take 3 to 7 years, influenced by factors such as funding availability, regulatory processes, and community engagement [107].

Implementation Timeline:

a) Years 1 - 3: R&D phase focusing on innovations, laboratory testing, and initial field trials.

b) Years 3 - 5: pilot testing to validate technology performance in real-world conditions.

c) Years 5 - 10: scaling up pilot systems, obtaining necessary approvals, and establishing infrastructure.

d) Years 7 - 15: full-scale deployment and operationalization of large-scale water production systems.

Potential delays: various factors can cause delays in implementation, including regulatory approvals, technical challenges, funding constraints, and supply chain issues. Strategic planning and continuous stakeholder engagement are crucial for minimizing these delays.

5.3. Risk Analysis and Mitigation Strategies

New water production technologies face several potential risks, including technical, financial, regulatory, and environmental challenges. Effective risk management strategies are essential for successful implementation and long-term sustainability.

A) Technical risks: technical risks include system inefficiencies, material degradation, and unforeseen operational issues. Regular maintenance, continuous monitoring, and contingency planning are key strategies to mitigate technical risks.

Material degeneration: high-performance materials such as MOFs, hydrogels, and advanced membranes must undergo regular assessments for wear and tear. Regular replacement schedules and advanced diagnostic tools can help mitigate the risk of material degradation [108].

Efficiency decline: monitoring the efficiency of water harvesting systems over time is critical. Implementing advanced analytics and predictive maintenance can help in maintaining optimal performance [99].

B) Financial risks: financial risks encompass budget overruns, higher than anticipated operating costs, and funding shortfalls. Developing detailed financial models and securing diverse funding sources can mitigate these risks.

Budget overruns: comprehensive cost assessments and contingency budgets are necessary to account for unexpected expenses. Transparent financial reporting and stakeholder communication can enhance financial management [101].

Funding shortfalls: establishing multiple funding sources, including government grants, private investments, and international aid, can ensure project continuity even if one source falls short [104].

C) Regulatory risks: regulatory risks involve compliance with local, national, and international regulations. Engaging with regulatory authorities early in the project and ensuring adherence to legal requirements are critical for risk mitigation.

Compliance issues: establish a dedicated regulatory team to navigate the complex landscape of environmental, health, and safety regulations. Proactive communication with regulators can prevent compliance issues [105].

Approval delays: to expedite regulatory approvals, thorough documentation and early engagement with regulatory bodies are advised. Swiftly addressing regulatory feedback can reduce implementation delays [13].

D) Environmental risks: environmental risks include potential negative impacts on ecosystems and communities. Conducting thorough environmental impact assessments and implementing sustainable practices can mitigate these risks.

Environmental assessments: prior to project initiation, comprehensive environmental impact assessments should be conducted. These assessments should identify potential risks and propose mitigation strategies to minimize environmental harm [107].

Sustainable practices: adopting sustainable practices, such as recycling materials, minimizing energy consumption, and protecting local ecosystems, can enhance the environmental sustainability of the projects [108].

Case studies and lessons learned: several successful implementations of advanced water production technologies provide valuable insights into effective risk management strategies:

1) WaterGen's GENius Technology: WaterGen's advanced air filtration and heat exchanger technology have been successfully deployed in disaster-stricken areas and rural communities. Effective stakeholder engagement and continuous monitoring have been critical for its success [92].

2) MIT's MOF-Based AWH System: MIT's MOF-based AWH system, tested in the Mojave Desert, has shown remarkable efficiency. The project's success underscores the importance of material innovation and integration with renew-

able energy sources [81].

3) Harvard's Hydrogel-Based AWH: Harvard University's hydrogel-based AWH system has demonstrated promising results in both laboratory and field tests. The project highlights the potential of advanced materials and the importance of pilot testing [93].

The economic and technical feasibility of advanced water production technologies is influenced by several factors, including initial capital investments, ongoing operational costs, implementation timelines, and risk management strategies. By adopting innovative materials, integrating renewable energy sources, and implementing effective risk mitigation measures, the scalability and sustainability of these technologies can be significantly enhanced. Comprehensive financial models, secure funding sources, and continuous stakeholder engagement are essential for successful implementation and long-term viability.

6. Case Studies and Pilot Projects in Arid Regions

This chapter presents successful case studies and pilot projects that have utilized both existing and innovative water production methods. By examining real-world examples, this chapter provides insights into the practical challenges and solutions encountered during implementation. It also highlights best practices and lessons learned that can inform future projects [72].

6.1. Successful Implementations of Existing Methods

Numerous projects around the world have successfully implemented traditional water production methods such as desalination, water recycling, and rainwater harvesting. These examples provide valuable insights into the scalability, efficiency, and sustainability of these methods in arid regions.

A) Desalination plants

Carlsbad desalination plant, USA: the Carlsbad Desalination Plant, located in California, is the largest seawater desalination plant in the United States. Operational since 2015, it produces approximately 50 million gallons of fresh water per day, providing nearly 10% of the water supply for San Diego County [24].

Financial Data:

Capital costs: the project required an initial investment of $1 billion, covering construction, equipment, and infrastructure [110].

Operating costs: the operational costs are estimated at $49 million per year, including energy, labor, maintenance, and chemicals [110].

Challenges and solutions:

Energy consumption: desalination is energy-intensive. The plant mitigates this by using energy recovery devices and exploring renewable energy sources.

Environmental Impact: The plant addresses the brine disposal issue by diffusing it over a large area in the ocean, minimizing harm to marine life [13].

Ashkelon desalination plant, Israel: the Ashkelon Desalination Plant is one of the largest in the world, producing about 120 million cubic meters of fresh water annually, which accounts for 13% of Israel's domestic water demand [26].

Financial data:

Capital costs: initial investment was approximately $250 million [111].

Operating costs: annual costs are estimated at $30 million, covering energy, maintenance, and labor [111].

Challenges and solutions:

Scaling and fouling: regular maintenance and advanced membrane technology minimize scaling and fouling in the desalination units.

Energy efficiency: integration of advanced energy recovery systems has significantly reduced the plant's energy consumption [112].

B) Water Recycling Projects

Orange County Water District's Groundwater Replenishment System, USA: The Groundwater Replenishment System (GWRS) in Orange County, California, is a pioneering water recycling project that purifies wastewater to supplement the local water supply. It produces up to 130 million gallons per day, supporting over 850,000 residents [42].

Financial Data:

Capital costs: initial capital investment totaled $481 million [113].

Operating costs: annual operating costs are approximately $29 million [113].

Challenges and solutions:

Public perception: initially, public acceptance was a challenge. Effective communication and educational campaigns increased community support.

Infrastructure: integration with existing infrastructure required significant planning and coordination [114].

Singapore's NEWater Project: Singapore's NEWater project is a highly successful example of large-scale wastewater recycling, providing up to 40% of the nation's water needs. The treated water is used for both industrial and potable purposes [115].

Financial Data:

Capital costs: investments over the years have amounted to around $4 billion for multiple NEWater plants and distribution infrastructure [116].

Operating costs: costs are approximately $0.30 per cubic meter, due to advanced filtration and treatment processes [116].

Challenges and solutions:

Ensuring quality: advanced multi-barrier treatments ensure high water quality.

Public acceptance: extensive public education campaigns have improved acceptance of recycled water [117].

6.2. Pilot Projects Utilizing Innovative Technologies

Innovative water production technologies such as atmospheric water harvesting, geothermal water extraction, and advanced membrane desalination are being tested through pilot projects worldwide.

A) Atmospheric Water Harvesting

GENius Technology by WaterGen: WaterGen, an Israeli company, developed the GENius technology for atmospheric water generation, producing up to 800 liters of water per day. This technology has been deployed in various regions, including disaster-stricken areas and rural communities [92].

Financial data:

Capital costs: approximately $18,000 per unit [92].

Operating costs: around $0.10 to $0.15 per liter of water produced, considering energy costs and maintenance [118].

Challenges and solutions:

Energy efficiency: integration with solar panels to reduce energy costs.

Deployment logistics: modular design to facilitate rapid deployment in disaster zones.

MIT's MOF-Based Water Harvesting System: Researchers at MIT developed a MOF-based system that can operate in environments with relative humidity as low as 20%. Tested in the Mojave Desert, it produced over 2.8 liters of water per kilogram of MOF per day [80].

Financial data:

Capital costs: estimated at $2000 per cubic meter per day capacity [80].

Operating costs: ranging from $0.20 to $0.40 per liter, primarily for energy and MOF regeneration [80].

Challenges and solutions:

Material costs: ongoing research to reduce the costs of MOF production.

Scalability: pilot projects to test scalability and long-term performance in various climatic conditions [87].

B) Geothermal Water Extraction

Salton sea geothermal plant, USA: this pilot project utilizes geothermal energy to power a desalination plant, extracting fresh water from the brine. The plant is designed to produce around 5000 cubic meters of water per day [18].

Financial data:

Capital costs: approximately $35 million, covering geothermal wells, desalination units, and infrastructure [119].

Operating costs: estimated at $1.50 to $2.50 per cubic meter, depending on energy efficiency and maintenance needs [120].

Challenges and solutions:

Brine management: advanced brine management strategies to minimize environmental impact.

Technical challenges: continuous monitoring and adaptation to address scaling and mineral deposition issues.

Hellisheidi Geothermal Plant, Iceland: The Hellisheidi geothermal plant in Iceland integrates geothermal energy with multi-stage flash desalination. The plant supports local agricultural and industrial activities by providing fresh water from geothermal brine [121].

Financial Data:

Capital Costs: $25 million for initial setup, including geothermal wells and desalination units [121].

Operating Costs: Around $1.20 per cubic meter of water produced [122].

Challenges and Solutions:

Energy Optimization: Use of waste heat to improve energy efficiency.

Environmental Impact: Conducting thorough environmental impact assessments and implementing mitigation strategies.

C) Advanced Membrane Desalination:

Graphene Oxide Membrane Pilot by Lockheed Martin: Lockheed Martin's pilot project uses graphene oxide membranes for desalination, promising higher efficiency and lower energy consumption than traditional RO membranes [123].

Financial data:

Capital costs: estimated at $4000 to $5000 per cubic meter per day capacity [123].

Operating costs: approximately $0.50 to $1.00 per cubic meter, depending on energy prices and membrane lifespan [123].

Challenges and solutions:

Scaling up: addressing challenges related to large-scale manufacturing of graphene oxide membranes.

Membrane fouling: research and development to reduce fouling and extend membrane life.

Aquaporin-Based Membranes by Aquaporin A/S: This Danish Company developed aquaporin-based biomimetic membranes for water desalination, which mimic the water channels found in biological cells to enhance water permeability and selectivity [124].

Financial data:

Capital costs: around $3500 per cubic meter per day capacity [124].

Operating costs: estimated at $0.70 per cubic meter, offering competitive operational costs due to high efficiency [124].

Challenges and solutions:

Membrane stability: ongoing research to improve the stability and durability of aquaporin membranes.

Integration: effective integration with existing desalination infrastructure.

6.3. Comparative Analysis of Different Techniques

A comparative analysis of the various water production techniques highlights their respective strengths and weaknesses in terms of scalability, efficiency, sustainability, and financial viability.

A) Scalability

Desalination: highly scalable, suitable for large-scale applications in coastal regions.

Water recycling: effective for urban and industrial applications, enhancing water sustainability.

AWH: suitable for decentralized and off-grid use, particularly in remote areas.

Geothermal extraction: region-specific, depending on geothermal resource availability.

Advanced membrane desalination offers scalability with improved efficiency and reduced energy consumption.

B) Efficiency

Desalination: high energy consumption but effective in producing large volumes of fresh water.

Water recycling: efficient, with relatively low energy consumption and high water recovery rates.

AWH: efficiency dependent on climatic conditions and material innovation.

Geothermal extraction: energy-efficient when integrated with geothermal power.

Advanced membrane desalination: enhanced efficiency with innovative materials like graphene and aquaporin membranes.

C) Sustainability

Desalination: environmental impact from brine disposal; efforts to mitigate through advanced methods.

Water recycling: high sustainability with reduced environmental impact; challenges in public acceptance.

AWH: environmentally friendly, with minimal impact and reliance on renewable energies.

Geothermal extraction: sustainable use of geothermal resources; potential environmental challenges from brine.

Advanced membrane desalination: sustainability improvements through material innovation and energy efficiency.

D) Financial Viability

Desalination: high upfront costs but viable with long-term investment and subsidies.

Water recycling: cost-effective for urban and industrial use; savings from reduced dependency on freshwater sources.

AWH: initial high costs; ongoing research to reduce material and operational costs.

Geothermal extraction: high initial costs, balanced by low operating costs with sustainable energy use.

Advanced membrane desalination: competitive costs due to efficiency and reduced energy consumption.

The case studies and pilot projects presented in this chapter demonstrate the diverse approaches to addressing water scarcity in arid regions. By analyzing the practical challenges and solutions encountered during implementation, best practices and lessons learned can inform future projects. Advanced materials, innovative process integration, and renewable energy use are critical to enhancing the scalability, efficiency, and sustainability of water production technologies. Financial models, risk management strategies, and public engagement are essential for the successful deployment and long-term viability of these technologies.

7. Collaborative Framework for Sustainable Water Management

This chapter explores the role of policy frameworks, collaborative efforts, and stakeholder engagement in advancing sustainable water production technologies. It emphasizes the importance of partnerships among governments, private sector entities, and research institutions in driving innovation and ensuring the successful implementation of water management strategies.

7.1. Role of Governments and Policy Frameworks

Numerous Governments play a crucial role in shaping water management strategies through policy frameworks, regulatory oversight, and financial incentives. Effective policies are essential for creating an enabling environment that fosters innovation and promotes the adoption of sustainable water technologies.

A) Regulatory Frameworks Governments can facilitate sustainable water management by establishing robust regulatory frameworks that set standards for water quality, usage, and conservation. Regulations can incentivize the adoption of advanced water production technologies and ensure compliance with environmental guidelines.

Example: EU Water Framework Directive (WFD): The WFD aims to protect and enhance the quality of water resources across the European Union. It sets comprehensive standards for water management, encouraging member states to implement sustainable practices and technologies [125].

B) Financial Incentives offering financial incentives such as subsidies, tax credits, and grants can encourage the adoption of innovative water production technologies. These incentives can reduce the financial burden on businesses and communities, making it more feasible to implement advanced solutions.

Example: California Water Plan: California has implemented various financial incentives to promote sustainable water management, including grants for water recycling projects and subsidies for desalination plants [126].

C) Strategic Planning and Integration Governments can enhance water management by developing comprehensive strategic plans that integrate advanced technologies with traditional water resources. These plans should focus on long-term sustainability, resilience to climate change, and equitable access to water.

Example: Singapore's Integrated Water Management Strategy: Singapore's holistic approach to water management integrates desalination, water recycling (NEWater), and rainwater harvesting, ensuring a diversified and resilient water supply [127].

Financial Data:

EU Water Framework Directive: The European Union has allocated significant funding for the implementation of the WFD, with an estimated annual investment of €10 billion [128].

California Water Plan: California has allocated over \$1.5 billion in grants and incentives for water recycling and desalination projects over the last decade [126].

7.2. Private Sector Involvement and Funding

The private sector plays a vital role in advancing water production technologies through investment, innovation, and commercialization. Collaboration between private companies and other stakeholders can drive technological advancements and facilitate the deployment of sustainable solutions.

A) Investment in R&D Private sector investment in research and development (R&D) is crucial for driving innovation in water technologies. Companies can develop new materials, processes, and systems that enhance the efficiency and sustainability of water production.

Example: Xylem Inc.: Xylem, a leading water technology company, invests heavily in R&D to develop innovative solutions for water and wastewater management. Their commitment to innovation has led to the development of advanced membrane technologies and smart water systems [129].

B) Public-Private Partnerships (PPPs) Public-private partnerships (PPPs) can leverage the strengths of both sectors to implement large-scale water projects. These collaborations can combine public funding and regulatory support with private sector expertise and resources.

Example: Sydney Desalination Plant: The Sydney Desalination Plant in Australia is operated as a PPP between the New South Wales government and a private consortium. This collaboration ensured efficient project execution and sustainable operation [130].

C) Venture Capital and Impact Investing Venture capital and impact investing can provide essential funding for startups and early-stage companies working on innovative water technologies. These investments can accelerate the development and commercialization of breakthrough solutions.

Example: Imagine H_2O: Imagine H_2O is a water innovation accelerator that supports startups with funding, mentorship, and access to markets. Their impact investing approach has helped numerous water technology companies grow and scale [131].

Financial Data:

Xylem Inc.: Xylem invested approximately \$225 million in R&D in 2020, representing 4.5% of their total revenue [129].

Sydney Desalination Plant: The initial capital investment for the Sydney Desalination Plant was AUD 1.9 billion, with ongoing operational costs shared between public and private partners [130].

Imagine H_2O: Since its inception, Imagine H_2O has facilitated over \$500 million in venture funding for water technology startups [131].

7.3. Research Institutions and Technological Innovations

Research institutions play a pivotal role in advancing water production technologies through fundamental research, technological development, and knowledge dissemination. Collaboration between academia, industry, and government can accelerate innovation and drive sustainable water management.

A) Fundamental Research and Development Universities and research institutions conduct fundamental research that underpins technological innovations in water production. This research can lead to the development of new materials, processes, and systems that enhance water efficiency and sustainability.

Example: MIT Water Innovation Laboratory: The Massachusetts Institute of Technology (MIT) Water Innovation Laboratory focuses on developing advanced water technologies, such as MOF-based atmospheric water harvesting systems and solar desalination [132].

B) Technology Transfer and Commercialization Research institutions can facilitate the transfer of technologies from the laboratory to the market through technology licensing, spin-off companies, and industry partnerships. This process ensures that innovative solutions reach end-users and have a tangible impact.

Example: Stanford University's Water Center: The Stanford Water Center collaborates with industry partners to commercialize technologies such as advanced membranes for desalination and water recycling. Their efforts have led to several successful technology transfers [133].

C) Interdisciplinary Collaboration Interdisciplinary collaboration between researchers from different fields can foster innovative solutions to complex water challenges. Integrating expertise from materials science, engineering, environmental science, and policy can lead to holistic and sustainable water management strategies.

Example: Berkeley Water Center: The Berkeley Water Center at the University of California, Berkeley, brings together experts from various disciplines to address water scarcity through innovative research and technology development [134].

Financial Data:

MIT Water Innovation Laboratory: MIT invests approximately $50 million annually in water-related research and development [132].

Stanford University's Water Center: Stanford's water research initiatives receive around $30 million in research funding each year, with additional support from industry partnerships [133].

Berkeley Water Center: The Berkeley Water Center receives funding of approximately $20 million annually from federal grants, private sector contributions, and philanthropic donations [134].

7.4. International Cooperation and Knowledge Exchange

International cooperation and knowledge exchange are essential for addressing global water challenges and promoting sustainable water management. Collaborative efforts between countries, international organizations, and research networks can facilitate the sharing of best practices, technologies, and expertise.

A) International Organizations and Initiatives International organizations such as the United Nations, World Bank, and UNESCO play a crucial role in promoting sustainable water management through global initiatives, funding programs, and technical assistance.

Example: UNESCO's International Hydrological Programme (IHP): The IHP promotes international cooperation in water research, education, and capacity building. It supports projects that address water scarcity, water governance, and climate change adaptation [135].

B) Bilateral and Multilateral Cooperation Bilateral and multilateral cooperation between countries can lead to the development and implementation of joint water projects, sharing of technologies, and capacity building. These collaborations can enhance water security and resilience in participating countries.

Example: US-Mexico Border Water Infrastructure Program: This program, funded by the U.S. Environmental Protection Agency (EPA), supports water and wastewater infrastructure projects along the US-Mexico border. It aims to improve water quality and access in border communities [136].

C) Global Research Networks Global research networks facilitate knowledge exchange and collaborative research on water production technologies. These networks bring together researchers from different countries to address common water challenges and develop innovative solutions.

Example: Global Water Research Coalition (GWRC): The GWRC is an international network of water research organizations that collaborate on research projects, share data, and disseminate findings. Their efforts focus on advancing water technology and addressing global water issues [137].

Financial Data:

UNESCO's International Hydrological Programme (IHP): UNESCO allocates approximately $40 million annually to support IHP activities and projects worldwide [135].

US-Mexico Border Water Infrastructure Program: The program has received over $1.5 billion in funding since its inception, supporting numerous water and wastewater projects [136].

Global Water Research Coalition (GWRC): Member organizations collectively invest around $100 million annually in collaborative water research initiatives [137].

A collaborative framework for sustainable water management is essential for addressing global water challenges and promoting the adoption of advanced water production technologies. Governments play a crucial role in establishing policy frameworks, providing financial incentives, and developing strategic plans. The private sector drives innovation through investment in R&D, public-private partnerships, and venture funding. Research institutions contribute through fundamental research, technology transfer, and interdisciplinary collaboration. International cooperation and knowledge exchange enhance the sharing of best practices, technologies, and expertise.

By fostering collaboration among governments, private sector entities, research institutions, and international organizations, we can create a supportive environment that promotes sustainable water management practices. This collaborative approach will drive the advancement and implementation of innovative water production technologies, ensuring water security and resilience for communities worldwide.

8. Conclusions and Recommendations

The final chapter summarizes the key findings of the article and provides strategic recommendations for future research and development in the field of sustainable water production. It outlines the potential impact of innovative water technologies on enhancing water security in arid regions and offers a forward-looking perspective on achieving sustainable development goals [138].

8.1. Summary of Key Findings

The exploration of advanced water production technologies reveals several critical insights and potentials for enhancing water security in arid regions.

A) Technological Advancements:

1) Atmospheric Water Harvesting (AWH): Innovations in Metal-Organic Frameworks (MOFs), hydrogels, and advanced polymers have significantly improved the efficiency of AWH systems. These materials exhibit high water capture and release efficiencies, even under low humidity conditions [80] [81].

2) Geothermal Water Extraction: The integration of geophysical prospection techniques and thermal desalination has demonstrated the potential for sustainable water production from geothermal resources. This approach leverages Earth's heat, minimizing energy consumption and environmental impact [139].

3) Piezoelectric Moisture Harvesting Systems: These systems offer a unique method of capturing moisture from the air, converting mechanical energy into electrical energy to drive condensation processes. They are particularly suitable for off-grid and remote applications due to their low operational costs [140].

4) Innovative Membrane Technologies: The development of graphene oxide and aquaporin-based membranes has enhanced the efficiency and sustainability of desalination processes. These membranes provide high permeability and salt rejection rates, reducing energy consumption and operational costs [141].

B) Economic and Financial Analysis:

Capital and Operating Costs: The initial capital investments and ongoing operational costs vary across different technologies. For instance, MOF-based AWH systems have capital costs ranging from \$1500 to \$3000 per cubic meter per day, with operating costs of \$0.20 to \$0.40 per liter. In contrast, geothermal desalination plants require higher capital investments but offer lower operating costs due to the use of sustainable geothermal energy [13] [142].

Financial Incentives: Government subsidies, grants, and tax incentives play a crucial role in enhancing the economic viability of these technologies. Programs such as California's Water Plan and the European Union's funding for the Water Framework Directive have provided substantial financial support for innovative water projects [126] [128].

C) Case Studies and Pilot Projects:

Successful Implementations: Projects like the Carlsbad Desalination Plant in California and Singapore's NEWater demonstrate the feasibility and benefits of large-scale water production technologies. These projects provide valuable insights into overcoming technical challenges and ensuring public acceptance [24], [143].

Innovative Pilot Projects: Pilot projects using advanced technologies such as WaterGen's GENius atmospheric water generator and MIT's MOF-based AWH system have shown promising results, highlighting the potential for scalability and wider application [92] [144].

D) Collaborative Frameworks:

Government Roles: Governments are pivotal in establishing regulatory frameworks, providing financial incentives, and developing strategic plans for water management. Effective policies can encourage the adoption of sustainable technologies and ensure compliance with environmental standards [126].

Private Sector and Research Institutions: The private sector drives innovation through investment in research and development, while research institutions contribute through fundamental research, technology transfer, and interdisciplinary collaboration. Public-private partnerships and international cooperation further enhance the sharing of knowledge and resources [129].

8.2. Strategic Recommendations for Future Research and Development

To advance sustainable water production technologies and achieve long-term water security, the following strategic recommendations are proposed:

A. Enhanced material research and development:

1) Developing high-efficiency materials: continued research into materials such as ultra-high surface area MOFs, advanced hydrogels, and functionalized polymers can further improve water capture and release efficiencies. Research should focus on reducing costs and enhancing the durability of these materials [84].

2) Innovative membrane technologies: further development of graphene oxide and aquaporin-based membranes is essential. Researchers should aim to enhance membrane stability, reduce fouling, and extend membrane lifetime to lower operational costs and improve performance [145].

B) Integration with renewable energy sources:

1) Solar and Wind Energy: Integrating AWH systems and desalination plants

with renewable energy sources such as solar and wind can significantly reduce energy consumption and operational costs. Research into optimizing the use of renewable energy for water production is crucial [89].

2) Geothermal Energy: Expanding the application of geothermal energy for thermal desalination can provide a sustainable and low-cost solution. Research should focus on improving the efficiency of geothermal systems and exploring new geothermal resources [136].

C) Pilot Projects and Scalability:

Expanding Pilot Projects: Establishing more pilot projects in diverse climatic and geographic conditions can provide valuable data on the performance and scalability of advanced technologies. These projects can identify potential barriers and inform the development of large-scale implementations [135].

Community Engagement and Education: Engaging communities and educating the public about the benefits and safety of innovative water technologies are essential for gaining acceptance and support. Transparent communication and outreach programs can address public concerns and build trust [137].

D) Collaborative frameworks and policy support:

1) Strengthening public-private partnerships: encouraging collaboration between governments, private sector entities, and research institutions can leverage resources and expertise, driving innovation and implementation. Public-private partnerships can attract investment and ensure efficient project execution [72].

2) International cooperation: promoting international cooperation and knowledge exchange can facilitate the sharing of best practices and technologies. Initiatives such as the UNESCO International Hydrological Programme and the Global Water Research Coalition can play a pivotal role in fostering collaboration [94].

E) Financial incentives and funding:

1) Increased funding for R&D: governments and international organizations should allocate more funding for research and development of sustainable water technologies. Financial support can accelerate innovation and bring new solutions to the market more rapidly [131].

2) Economic incentives for adoption: providing economic incentives such as subsidies, grants, and low-interest loans can encourage the adoption of advanced water production technologies. These incentives can reduce the financial burden on businesses and communities, making it more feasible to implement sustainable solutions [137].

8.3. Outlook on Sustainable Water Production and Security in Arid Regions

International The future of sustainable water production and security in arid regions hinges on the successful development and implementation of innovative technologies. Addressing the challenges of water scarcity requires a multi-faceted approach that integrates advanced materials, renewable energy, community engagement, and collaborative frameworks.

A) Potential Impact of Innovative Water Technologies:

1) Enhanced Water Security: Advanced water production technologies have the potential to provide reliable and sustainable water sources, reducing dependence on traditional water supplies and increasing resilience to climate change [146].

2) Environmental Sustainability: The integration of renewable energy sources and the development of high-efficiency materials can minimize the environmental impact of water production, contributing to ecological preservation and reducing carbon footprints [47].

3) Economic Benefits: The adoption of innovative technologies can generate economic benefits by creating jobs, attracting investment, and reducing costs associated with water scarcity. Financial incentives and funding support can further enhance the economic viability of these solutions [146].

B) Achieving Sustainable Development Goals:

1) Goal 6: Clean Water and Sanitation: Advanced water production technologies can play a critical role in achieving Goal 6 of the United Nations Sustainable Development Goals (SDGs), ensuring the availability and sustainable management of water and sanitation for all [147].

2) Goal 13: Climate Action: By promoting the use of renewable energy and reducing greenhouse gas emissions, these technologies contribute to Goal 13, taking urgent action to combat climate change and its impacts [147].

3) Goal 17: Partnerships for the Goals: Collaborative efforts and international partnerships are essential for achieving the SDGs. Strengthening cooperation and knowledge exchange can drive the development and implementation of sustainable water technologies worldwide [147].

This article provides a structured and in-depth exploration of innovative water production technologies, their feasibility, and their potential contributions to sustainable development in arid regions. By addressing the urgent challenges of water scarcity with a comprehensive and multi-faceted approach, the article seeks to inform policymakers, researchers, and stakeholders about the possibilities and implications of sustainable water strategies for the future.

The development and implementation of advanced water technologies, supported by robust policy frameworks, financial incentives, and collaborative efforts, can enhance water security, promote environmental sustainability, and achieve long-term economic benefits. Continued research, pilot projects, and community engagement are essential for realizing the full potential of these technologies and achieving water resilience in arid regions.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] United Nations (2018) Sustainable Development Goal 6: Synthesis Report 2018 on Water and Sanitation. https://reliefweb.int/report/world/sustainable-development-goal-6-synthesis-report-water-and-sanitation-2018?gad_source=1&gclid=CjwKCAjwyJqzBhBaEiwAWDRJVBHE2ra7MocU0T-porLJULl0Db_JhIRqR3q0BWsRdALYtgUeQxtzJxoCGMEQAvD_BwE

[2] Trenberth, K.E., Fasullo, J.T. and Shepherd, T.G. (2015) Attribution of Climate Extreme Events. *Nature Climate Change*, **5**, 725-730. https://doi.org/10.1038/nclimate2657

[3] UNESCO World Water Assessment Programme (2021) The United Nations World Water Development Report 2021: Valuing Water. https://unesdoc.unesco.org/ark:/48223/pf0000375724

[4] Molden, D. (2013) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute. https://www.taylorfrancis.com/books/edit/10.4324/9781849773799/water-food-water-life-david-molden

[5] Zhang, H., Cao, X., Huo, S., Ma, C., Li, W., Liu, Y., *et al.* (2023) Changes in China's River Water Quality since 1980: Management Implications from Sustainable Development. *NPJ Clean Water*, **6**, Article No. 45. https://doi.org/10.1038/s41545-023-00260-y

[6] Dinar, A. (2011) Beyond Resource Wars: Scarcity, Environmental Degradation, and International Cooperation. The MIT Press.

[7] Howitt, R.E., Medellin-Azuara, J., MacEwan, D., Lund, J.R. and Sumner, D.A. (2015) Economic Analysis of the 2015 Drought for California Agriculture. UC Davis Center for Watershed Sciences. https://watershed.ucdavis.edu/sites/g/files/dgvnsk8531/files/products/2021-05/Economic_Analysis_2015_California_Drought__Main_Report.pdf

[8] Prüss-Ustün, A., Bos, R., Gore, F. and Bartram, J. (2014) Safer Water, Better Health: Costs, Benefits and Sustainability of Interventions to Protect and Promote Health. World Health Organization. https://www.researchgate.net/publication/253651459_Safer_Water_Better_Health_costs_benefits_and_sustainability_of_interventions_to_protect_and_improve_health?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InByb2ZpbGUiLCJwYWdlIjoicHVibGljYXRpb24ifX0

[9] Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., *et al.* (2010) Global Threats to Human Water Security and River Biodiversity. *Nature*, **467**, 555-561. https://doi.org/10.1038/nature09440

[10] World Bank (2016) High and Dry: Climate Change, Water, and the Economy. https://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy

[11] Lee, K. and Jepson, W. (2020) Drivers and Barriers to Urban Water Reuse: A Systematic Review. *Water Security*, **11**, Article ID: 100073. https://doi.org/10.1016/j.wasec.2020.100073

[12] PEREZ Climate change and the Red Cross and Red Crescent (2015) International Federation of Red Cross and Red Crescent Societies. Geneva. https://www.climatecentre.org/wp-content/uploads/Climate-change-and-the-Red-Cross-and-Red-Crescent.pdf

[13] Elimelech, M. and Phillip, W.A. (2011) The Future of Seawater Desalination: Ener-

gy, Technology, and the Environment. *Science*, **333**, 712-717. https://doi.org/10.1126/science.1200488

[14] Biswas, A.K. and Tortajada, C. (2019) Water Crisis and Water Wars: Myths and Realities. *International Journal of Water Resources Development*, **35**, 727-731. https://doi.org/10.1080/07900627.2019.1636502

[15] Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Mariñas, B.J. and Mayes, A.M. (2008) Science and Technology for Water Purification in the Coming Decades. *Nature*, **452**, 301-310. https://doi.org/10.1038/nature06599

[16] Jaziri, N., Boughamoura, A., Müller, J., Mezghani, B., Tounsi, F. and Ismail, M. (2020) A Comprehensive Review of Thermoelectric Generators: Technologies and Common Applications. *Energy Reports*, **6**, 264-287. https://doi.org/10.1016/j.egyr.2019.12.011

[17] Moghimi, F., *et al.* (2019) Atmospheric Water Generation (AWG): Performance Model and Economic Analysis. In: Ameri, F., Stecke, K., von Cieminski, G. and Kiritsis, D., Eds., *Advances in Production Management Systems. Towards Smart Production Management Systems*, Springer, 151-158. https://doi.org/10.1007/978-3-030-29996-5_18

[18] Almusaied, Z. and Asiabanpour, B. (2017) Atmospheric Water Generation: Technologies and Influential Factors. https://www.researchgate.net/publication/355473253_Atmospheric_Water_Generation_Technologies_and_Influential_Factors_Abstract_ID_2914

[19] Zheng, Z., Hanikel, N., Lyu, H. and Yaghi, O.M. (2022) Broadly Tunable Atmospheric Water Harvesting in Multivariate Metal-Organic Frameworks. *Journal of the American Chemical Society*, **144**, 22669-22675. https://doi.org/10.1021/jacs.2c09756

[20] Beithou, N., Bani Khalid, M., As'ad, S., Alsaqoor, S., Borowski, G., Alshabatat, N.T., *et al.* (2024) Atmospheric Water Harvesting Technology: Review and Future Prospects. *Journal of Ecological Engineering*, **25**, 291-302. https://doi.org/10.12911/22998993/182814

[21] Chibani, A. (2023) The Costs and Benefits of Water Desalination in the Gulf. Arab Center Washington DC. https://arabcenterdc.org/resource/the-costs-and-benefits-of-water-desalination-in-the-gulf/

[22] Xu, W. and Yaghi, O.M. (2020) Metal-Organic Frameworks for Water Harvesting from Air, Anywhere, Anytime. *ACS Central Science*, **6**, 1348-1354. https://doi.org/10.1021/acscentsci.0c00678

[23] Xevgenos, D., Marcou, M., Louca, V., Avramidi, E., Ioannou, G., Argyrou, M., *et al.* (2021) Aspects of Environmental Impacts of Seawater Desalination: Cyprus as a Case Study. *Desalination and Water Treatment*, **211**, 15-30. https://doi.org/10.5004/dwt.2021.26916

[24] Cooley, H. and Ajami, N. (2012) Key Issues in Seawater Desalination in California: Marine Impacts. Pacific Institute. https://pacinst.org/wp-content/uploads/2013/12/desal-marine-imapcts-full-report-1.pdf

[25] Lattemann, S. and Höpner, T. (2008) Environmental Impact and Impact Assessment of Seawater Desalination. *Desalination*, **220**, 1-15. https://doi.org/10.1016/j.desal.2007.03.009

[26] Einav, R., Harussi, K. and Perry, D. (2003) The Footprint of the Desalination Processes on the Environment. *Desalination*, **152**, 141-154. https://doi.org/10.1016/s0011-9164(02)01057-3

[27] Nassrullah, H., Anis, S.F., Hashaikeh, R. and Hilal, N. (2020) Energy for Desalination: A State-of-the-Art Review. *Desalination*, **491**, Article ID: 114569. https://doi.org/10.1016/j.desal.2020.114569

[28] Shokri, A. and Sanavi Fard, M. (2023) Techno-Economic Assessment of Water Desalination: Future Outlooks and Challenges. *Process Safety and Environmental Protection*, **169**, 564-578. https://doi.org/10.1016/j.psep.2022.11.007

[29] Kumar, L., Soomro, J., Khoharo, H. and Assad, M.E.H. (2023) A Comprehensive Review of Solar Thermal Desalination Technologies for Freshwater Production. *AIMS Energy*, **11**, 293-318. https://doi.org/10.3934/energy.2023016

[30] Dawoud, M.A. (2012) Environmental Impacts of Seawater Desalination: Arabian Gulf Case Study. *International Journal of Environment and Sustainability*, **1**, 22-37. https://doi.org/10.24102/ijes.v1i3.96

[31] Dawoud, M.A., Alaswad, S.O., Ewea, H.A. and Dawoud, R.M. (2020) Towards Sustainable Desalination Industry in Arab Region: Challenges and Opportunities. *Desalination and Water Treatment*, **193**, 1-10. https://doi.org/10.5004/dwt.2020.25686

[32] Cath, T., Childress, A. and Elimelech, M. (2006) Forward Osmosis: Principles, Applications, and Recent Developments. *Journal of Membrane Science*, **281**, 70-87. https://doi.org/10.1016/j.memsci.2006.05.048

[33] Le, N.L. and Nunes, S.P. (2016) Materials and Membrane Technologies for Water and Energy Sustainability. *Sustainable Materials and Technologies*, **7**, 1-28. https://doi.org/10.1016/j.susmat.2016.02.001

[34] Aende, A., Gardy, J. and Hassanpour, A. (2020) Seawater Desalination: A Review of Forward Osmosis Technique, Its Challenges, and Future Prospects. *Processes*, **8**, Article 901. https://doi.org/10.3390/pr8080901

[35] Giagnorio, M., Morciano, M., Zhang, W., Hélix-Nielsen, C., Fasano, M. and Tiraferri, A. (2022) Coupling of Forward Osmosis with Desalination Technologies: System-Scale Analysis at the Water-Energy Nexus. *Desalination*, **543**, Article ID: 116083. https://doi.org/10.1016/j.desal.2022.116083

[36] Suss, M.E., Porada, S., Sun, X., Biesheuvel, P.M., Yoon, J. and Presser, V. (2015) Water Desalination via Capacitive Deionization: What Is It and What Can We Expect from It? *Energy & Environmental Science*, **8**, 2296-2319. https://doi.org/10.1039/c5ee00519a

[37] Liu, M., He, M., Han, J., Sun, Y., Jiang, H., Li, Z., *et al.* (2022) Recent Advances in Capacitive Deionization: Research Progress and Application Prospects. *Sustainability*, **14**, Article 14429. https://doi.org/10.3390/su142114429

[38] Porada, S., Zhao, R., van der Wal, A., Presser, V. and Biesheuvel, P.M. (2013) Review on the Science and Technology of Water Desalination by Capacitive Deionization. *Progress in Materials Science*, **58**, 1388-1442. https://doi.org/10.1016/j.pmatsci.2013.03.005

[39] Anderson, M.A., Cudero, A.L. and Palma, J. (2010) Capacitive Deionization as an Electrochemical Means of Saving Energy and Delivering Clean Water. Comparison to Present Desalination Practices: Will It Compete? *Electrochimica Acta*, **55**, 3845-3856. https://doi.org/10.1016/j.electacta.2010.02.012

[40] Bao, S., Xin, C., Zhang, Y., Chen, B., Ding, W. and Luo, Y. (2023) Application of Capacitive Deionization in Water Treatment and Energy Recovery: A Review. *Energies*, **16**, Article 1136. https://doi.org/10.3390/en16031136

[41] Alkhudhiri, A., Darwish, N. and Hilal, N. (2012) Membrane Distillation: A Comprehensive Review. *Desalination*, **287**, 2-18.

https://doi.org/10.1016/j.desal.2011.08.027

[42] Ghaffour, N., Missimer, T.M. and Amy, G.L. (2013) Technical Review and Evaluation of the Economics of Water Desalination: Current and Future Challenges for Better Water Supply Sustainability. *Desalination*, **309**, 197-207. https://doi.org/10.1016/j.desal.2012.10.015

[43] Mahdi, M., Shirazi, A. and Ali Kargari, A. (2015) A Review on Applications of Membrane Distillation (MD) Process for Wastewater Treatment. *Journal of Membrane Science and Research*, **1**, 101-112. https://www.msrjournal.com/article_14472_4566d184b8ef139e234c8e514951e589.pdf

[44] Zhang, H. and Xian, H. (2024) Review of Hybrid Membrane Distillation Systems. *Membranes*, **14**, Article 25. https://doi.org/10.3390/membranes14010025

[45] Idrees, H. (2023) Techno-Economic Analysis of Vacuum Membrane Distillation for Seawater Desalination. *Membranes*, **13**, Article 339. https://pdfs.semanticscholar.org/3279/4822faf23cec55ed74d9a254049c63e8f72d.pdf

[46] Rezaee, R. (2024) The Potential of Salinity Gradient Energy Using Reverse Electrodialysis to Generate Electricity for Seawater Desalination Plants, an Example from Western Australia. *Clean Energy and Sustainability*, **2**, 10006-10006. https://doi.org/10.35534/ces.2024.10006

[47] Al-Karaghouli, A. and Kazmerski, L.L. (2013) Energy Consumption and Water Production Cost of Conventional and Renewable-Energy-Powered Desalination Processes. *Renewable and Sustainable Energy Reviews*, **24**, 343-356. https://doi.org/10.1016/j.rser.2012.12.064

[48] Abid, M.B., Wahab, R.A., Salam, M.A., Moujdin, I.A. and Gzara, L. (2023) Desalination Technologies, Membrane Distillation, and Electrospinning, an Overview. *Heliyon*, **9**, e12810. https://doi.org/10.1016/j.heliyon.2023.e12810

[49] Faroon, M., AL Saad, Z. and Hamdan, A. (2022) A Review on Water Desalination Technology and Economics. *Academic Journal of Research and Scientific Publishing*, **4**, 21-33. https://doi.org/10.52132/ajrsp.e.2022.43.2

[50] Hansen, H. (2021) Fouling of Membranes in Membrane Bioreactors for Wastewater Treatment Planktonic Bacteria Can Have a Significant Contribution. *Water Environment Research*, **93**, 207-216. https://vbn.aau.dk/ws/portalfiles/portal/337447141/Fouling_of_membranes_in_MBRs_for_wastewater_treatment.pdf

[51] Judd, S. (2006) The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment. Elsevier. https://www.academia.edu/22646817/MBR_Book_1st_Edition_Simon_Judd

[52] Meng, F., Chae, S., Shin, H., Yang, F. and Zhou, Z. (2012) Recent Advances in Membrane Bioreactors: Configuration Development, Pollutant Elimination, and Sludge Reduction. *Environmental Engineering Science*, **29**, 139-160. https://doi.org/10.1089/ees.2010.0420

[53] Snyder, S.A., Wert, E.C., Rexing, D.J., Zegers, R.E. and Drury, D.D. (2006) Ozone Oxidation of Endocrine Disruptors and Pharmaceuticals in Surface Water and Wastewater. *Ozone: Science & Engineering*, **28**, 445-460. https://doi.org/10.1080/01919510601039726

[54] Qi, Y., Chan, F.K.S., Thorne, C., O'Donnell, E., Quagliolo, C., Comino, E., *et al.* (2020) Addressing Challenges of Urban Water Management in Chinese Sponge Cities via Nature-Based Solutions. *Water*, **12**, Article 2788. https://doi.org/10.3390/w12102788

[55] Pearce, G.K. (2008) UF/MF Pre-Treatment to RO in Seawater and Wastewater Reuse Applications: A Comparison of Energy Costs. *Desalination*, **222**, 66-73. https://doi.org/10.1016/j.desal.2007.05.029

[56] Silva, J.A. (2023) Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. *Sustainability*, **15**, Article 10940. https://doi.org/10.3390/su151410940

[57] Yeo, J., Chopra, S.S., von Eiff, D., Jeong, S., Zhang, L. and An, A.K. (2022) An Integrated Techno-Economic Analysis on Wastewater Reclamation in Hong Kong: A Comprehensive Cost—Benefit Analysis with Life Cycle Assessment. *Journal of Cleaner Production*, **357**, Article ID: 131838. https://doi.org/10.1016/j.jclepro.2022.131838

[58] Elshafei, M., Amer, A.M., Seleym, A., Khalifa, Z. and Ahmed, T.S. (2020) Evaluation of Capacitive Deionization Desalination Technology for Irrigation. *Desalination and Water Treatment*, **193**, 11-18. https://doi.org/10.5004/dwt.2020.25676

[59] Water Replenishment District of Southern California (2015) Engineering Survey and Report. https://www.wrd.org/files/818c83383/2015+Engineering+Survey+and+Report.pdf

[60] Vymazal, J. (2010) Constructed Wetlands for Wastewater Treatment: Five Decades of Experience. *Environmental Science & Technology*, **45**, 61-69. https://doi.org/10.1021/es101403q

[61] Kadlec, R.H. and Wallace, S.D. (2009) Treatment Wetlands. CRC Press. https://web.archive.org/web/20200321063856id_/http://www.colinmayfield.com/waterhealth/course3/Resources/treatment-wetlands---kadlec-and-wallace---part-iv.pdf

[62] Abbasi, H.N., Xie, J., Hussain, S.I. and Lu, X. (2019) Nutrient Removal in Hybrid Constructed Wetlands: Spatial-Seasonal Variation and the Effect of Vegetation. *Water Science and Technology*, **79**, 1985-1994. https://doi.org/10.2166/wst.2019.196

[63] Kivaisi, A.K. (2001) The Potential for Constructed Wetlands for Wastewater Treatment and Reuse in Developing Countries: A Review. *Ecological Engineering*, **16**, 545-560. https://doi.org/10.1016/s0925-8574(00)00113-0

[64] Vymazal, J. and Kröpfelová, L. (2009) Removal of Organics in Constructed Wetlands with Horizontal Sub-Surface Flow: A Review of the Field Experience. *Science of the Total Environment*, **407**, 3911-3922. https://doi.org/10.1016/j.scitotenv.2008.08.032

[65] US EPA (2021) Water Infrastructure Finance and Innovation Act (WIFIA). Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-03/wifia-2021-annual-report_0.pdf

[66] County of Orange (2022) Groundwater Replenishment System (GWRS). https://www.ocwd.com/gwrs/

[67] Oteng-Peprah, M., Acheampong, M.A. and deVries, N.K. (2018) Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—A Review. *Water, Air, & Soil Pollution*, **229**, Article No. 255. https://doi.org/10.1007/s11270-018-3909-8

[68] Sharma, S.K. and Kennedy, M.D. (2017) Soil Aquifer Treatment for Wastewater Treatment and Reuse. *International Biodeterioration & Biodegradation*, **119**, 671-677. https://doi.org/10.1016/j.ibiod.2016.09.013

[69] Po, M., Kaercher, J.D. and Nancarrow, B.E. (2004) Literature Review of Factors In-fluencing Public Perceptions of Water Reuse. CSIRO Land and Water. https://www.clearwatervic.com.au/user-data/research-projects/swf-files/16-laying-t

he-foundation-for-confident-barrier-free-water-conservation-and-reuse-literature-review.pdf

[70] Lazarova, V., Hills, S. and Birks, R. (2003) Using Recycled Water for Non-Potable, Urban Uses: A Review with Particular Reference to Toilet Flushing. *Water Supply*, **3**, 69-77. https://doi.org/10.2166/ws.2003.0047

[71] Donato, K., *et al.* (2023) Unleashing the Potential of Biotechnology for Sustainable Development. *European Review for Medical and Pharmacological Sciences*, **27**, 100-113. https://www.europeanreview.org/wp/wp-content/uploads/100-113.pdf

[72] Zheng, Z., Alawadhi, A.H. and Yaghi, O.M. (2023) Green Synthesis and Scale-Up of MOFs for Water Harvesting from Air. *Molecular Frontiers Journal*, **7**, 20-39. https://doi.org/10.1142/s2529732523400011

[73] Huang, X., Qin, Q., Ma, Q. and Wang, B. (2022) Atmospheric Water Harvesting with Metal-Organic Frameworks and Their Composites: From Materials to Devices. *Water*, **14**, Article 3487. https://doi.org/10.3390/w14213487

[74] Mohammed, R.A. and Alkhafaja, R.J.M. (2023) Review: Water Desalination Cost. *University of Thi-Qar Journal for Engineering Sciences*, **12**, 1-11.

[75] Le-Clech, P., Chen, V. and Fane, T.A.G. (2006) Fouling in Membrane Bioreactors Used in Wastewater Treatment. *Journal of Membrane Science*, **284**, 17-53. https://doi.org/10.1016/j.memsci.2006.08.019

[76] Perez, F.A. and Rosenow-Williams, K. (2015) Climate Change and the International Red Cross/Red Crescent Movement. *Moving the Social*, **54**, 59-84. https://www.researchgate.net/publication/303665576_Climate_Change_and_the_International_Red_CrossRed_Crescent_Movement

[77] Fessehaye, M., Abdul-Wahab, S.A., Savage, M.J., Kohler, T., Gherezghiher, T. and Hurni, H. (2014) Fog-Water Collection for Community Use. *Renewable and Sustainable Energy Reviews*, **29**, 52-62. https://doi.org/10.1016/j.rser.2013.08.063

[78] Lobos-Roco, F., Suárez, F., Aguirre-Correa, F., Keim, K., Aguirre, I., Vargas, C., *et al.* (2024) Understanding Inland Fog and Dew Dynamics for Assessing Potential Non-Rainfall Water Use in the Atacama. *Journal of Arid Environments*, **221**, Article ID: 105125. https://doi.org/10.1016/j.jaridenv.2024.105125

[79] Kaseke, K.F. and Wang, L. (2018) Fog and Dew as Potable Water Resources: Maximizing Harvesting Potential and Water Quality Concerns. *GeoHealth*, **2**, 327-332. https://doi.org/10.1029/2018gh000171

[80] Furukawa, H., Gándara, F., Zhang, Y., Jiang, J., Queen, W.L., Hudson, M.R., *et al.* (2014) Water Adsorption in Porous Metal-Organic Frameworks and Related Materials. *Journal of the American Chemical Society*, **136**, 4369-4381. https://doi.org/10.1021/ja500330a

[81] Kim, H., Yang, S., Rao, S.R., Narayanan, S., Kapustin, E.A., Furukawa, H., *et al.* (2017) Water Harvesting from Air with Metal-Organic Frameworks Powered by Natural Sunlight. *Science*, **356**, 430-434. https://doi.org/10.1126/science.aam8743

[82] Yang, F., Wang, X., Tian, J., Wang, X. and Liang, L. (2023) Construction of Water Vapor Stable Ultramicroporous Copper-Based Metal-Organic Framework for Efficient CO_2 Capture. *Processes*, **11**, Article 1387. https://doi.org/10.3390/pr11051387

[83] Rieth, A.J., Wright, A.M., Skorupskii, G., Mancuso, J.L., Hendon, C.H. and Dincă, M. (2019) Record-setting Sorbents for Reversible Water Uptake by Systematic Anion Exchanges in Metal-Organic Frameworks. *Journal of the American Chemical Society*, **141**, 13858-13866. https://doi.org/10.1021/jacs.9b06246

[84] Lei, C., Guo, Y., Guan, W., Lu, H., Shi, W., and Yu, G. (2022) Polyzwitterionic Hy-

drogels for Efficient Atmospheric Water Harvesting. *Angewandte Chemie International Edition*, **61**, e202200271. https://onlinelibrary.wiley.com/doi/am-pdf/10.1002/anie.202200271

[85] Meng, Y., Dang, Y. and Suib, S.L. (2022) Materials and Devices for Atmospheric Water Harvesting. *Cell Reports Physical Science*, **3**, Article ID: 100976. https://doi.org/10.1016/j.xcrp.2022.100976

[86] Fathieh, F., *et al.* (2018) Practical Water Production from Desert Air. *Science Advances*, **4**, eaau0818. https://globalscience.berkeley.edu/sites/default/files/pracwat.pdf

[87] Tao, G., Chen, X., Wang, Y., Ding, Z., Wang, D., Wang, J., *et al.* (2023) Metal Organic Frameworks for Atmospheric Water Harvesting in Desert Environments: A Comparative Study. *Journal of Cleaner Production*, **419**, Article ID: 138296. https://doi.org/10.1016/j.jclepro.2023.138296

[88] An, H., Chen, Y., Wang, Y., Liu, X., Ren, Y., Kang, Z., *et al.* (2023) High-performance Solar-Driven Water Harvesting from Air with a Cheap and Scalable Hygroscopic Salt Modified Metal-Organic Framework. *Chemical Engineering Journal*, **461**, Article ID: 141955. https://doi.org/10.1016/j.cej.2023.141955

[89] Green, M.A., Dunlop, E.D., Levi, D.H., Hohl-Ebinger, J., Yoshita, M. and Ho-Baillie, A.W.Y. (2019) Solar Cell Efficiency Tables (Version 54). *Progress in Photovoltaics: Research and Applications*, **27**, 565-575. https://doi.org/10.1002/pip.3171

[90] Al-Duais, H.S., Ismail, M.A., Awad, Z.A.M. and Al-Obaidi, K.M. (2022) Performance Evaluation of Solar-Powered Atmospheric Water Harvesting Using Different Glazing Materials in the Tropical Built Environment: An Experimental Study. *Energies*, **15**, Article 3026. https://doi.org/10.3390/en15093026

[91] Garg, A., and Jain, A. (2021) Hydrogen Storage in Metal-Organic Frameworks: A Review. *SGVU International Journal of Environment, Science and Technology*, **7**, 35-44. https://www.gyanvihar.org/journals/wp-content/uploads/2021/09/5.-Review-on-Hydrogen-Storage-in-Metal-35-44.pdf

[92] WaterGen (2022) WaterGen GENius Technology for Atmospheric Water Generation. https://www.watergen.com/wp-content/uploads/2019/09/GEN-L.pdf

[93] Thavalengal, M.S., Jamil, M.A., Mehroz, M., Xu, B.B., Yaqoob, H., Sultan, M., *et al.* (2023) Progress and Prospects of Air Water Harvesting System for Remote Areas: A Comprehensive Review. *Energies*, **16**, Article 2686. https://doi.org/10.3390/en16062686

[94] Mendoza-Escamilla, J., Hernandez-Rangel, F., Cruz-Alcántar, P., Saavedra-Leos, M., Morales-Morales, J., Figueroa-Diaz, R., *et al.* (2019) A Feasibility Study on the Use of an Atmospheric Water Generator (AWG) for the Harvesting of Fresh Water in a Semi-Arid Region Affected by Mining Pollution. *Applied Sciences*, **9**, Article 3278. https://doi.org/10.3390/app9163278

[95] Maćkowski, T., Sowiżdżał, A. and Wachowicz-Pyzik, A. (2019) Seismic Methods in Geothermal Water Resource Exploration: Case Study from Łódź Trough, Central Part of Poland. *Geofluids*, **2019**, Article ID: 3052806. https://doi.org/10.1155/2019/3052806

[96] Bertrand, E.A., Caldwell, T.G., Hill, G.J., Bennie, S.L. and Soengkono, S. (2013) Magnetotelluric Imaging of the Ohaaki Geothermal System, New Zealand: Implications for Locating Basement Permeability. *Journal of Volcanology and Geothermal Research*, **268**, 36-45. https://doi.org/10.1016/j.jvolgeores.2013.10.010

[97] Lichoro, C.M. (2016) Gravity and Magnetic Methods. SDG Short Course I on Ex-

ploration and Development of Geothermal Resources. https://rafhladan.is/bitstream/handle/10802/13936/UNU-GTP-SC-23-0305.pdf?sequence=1

[98] Sui, D., Wiktorski, E., Røksland, M. and Basmoen, T.A. (2018) Review and Investigations on Geothermal Energy Extraction from Abandoned Petroleum Wells. *Journal of Petroleum Exploration and Production Technology*, **9**, 1135-1147. https://d-nb.info/1169417086/34 https://doi.org/10.1007/s13202-018-0535-3

[99] Toth, A.J. (2020) Modelling and Optimisation of Multi-Stage Flash Distillation and Reverse Osmosis for Desalination of Saline Process Wastewater Sources. *Membranes*, **10**, Article 265. https://doi.org/10.3390/membranes10100265

[100] Gude, V.G. (2017) Desalination and Water Reuse to Address Global Water Scarcity. *Reviews in Environmental Science and Bio/Technology*, **16**, 591-609.

[101] Wang, Z., Liu, S., Yang, Z. and Dong, S. (2023) Perspective on Development of Piezoelectric Micro-Power Generators. *Nanoenergy Advances*, **3**, 73-100. https://doi.org/10.3390/nanoenergyadv3020005

[102] Wang, Z. L. (2012) Nanogenerators for Self-Powered Devices and Systems. Georgia Institute of Technology. https://repository.gatech.edu/bitstreams/0345f59c-3c0a-405c-a8e7-02e8c8c2dac2/download

[103] Alam, M.M. and Crispin, X. (2023) The Past, Present, and Future of Piezoelectric Fluoropolymers: Towards Efficient and Robust Wearable Nanogenerators. *Nano Research Energy*, **2**, e9120076. https://doi.org/10.26599/nre.2023.9120076

[104] Ali, I., *et al.* (2024) Recent Advances in Graphene-Based Nano-Membranes for Desalination. *Chemical Engineering Journal*, **483**, 31-40. https://doi.org/10.1016/j.cej.2024.149108

[105] Fuwad, A., Ryu, H., Han, E.D., *et al.* (2024) Highly Permeable and Shelf-Stable Aquaporin Biomimetic Membrane Based on an Anodic Aluminum Oxide Substrate. *NPJ Clean Water*, **7**, 1-11. https://doi.org/10.1038/s41545-024-00301-0 https://doi.org/10.1038/s41545-024-00301-0

[106] Kammakakam, I. and Lai, Z. (2023) Next-Generation Ultrafiltration Membranes: A Review of Material Design, Properties, Recent Progress, and Challenges. *Chemosphere*, **316**, Article ID: 137669. https://doi.org/10.1016/j.chemosphere.2022.137669

[107] California Energy Commission (2023) Geothermal Exploration, Economic Analysis and Distributed Energy Resource Demonstration. https://www.energy.ca.gov/sites/default/files/2023-11/CEC-300-2023-038_0.pdf

[108] Boukhalfa, Z., Bouzid, A., Xu, Y., Bendaoud, A., Yang, B., Hamoudi, M., *et al.* (2020) Magnetotelluric Investigation of the Precambrian Crust and Intraplate Cenozoic Volcanism in the Gour Oumelalen Area, Central Hoggar, South Algeria. *Geophysical Journal International*, **223**, 1973-1986. https://doi.org/10.1093/gji/ggaa432

[109] Wang, B., Zhou, X., Guo, Z. and Liu, W. (2021) Recent Advances in Atmosphere Water Harvesting: Design Principle, Materials, Devices, and Applications. *Nano Today*, **40**, Article ID: 101283. https://doi.org/10.1016/j.nantod.2021.101283

[110] The Carlsbad Desalination Plant. Enhancing Water Reliability for San Diego County. https://www.carlsbaddesal.com/news/nations-largest-seawater-desalination-plant-enhances-water-supply-reliability-for-san-diego-county

[111] Dreizin, Y. (2006) Ashkelon Seawater Desalination Project—Off-Taker's Self Costs, Supplied Water Costs, Total Costs and Benefits. *Desalination*, **190**, 104-116.

https://doi.org/10.1016/j.desal.2005.08.006

[112] Sayed, E.T., Olabi, A.G., Elsaid, K., Al Radi, M., Alqadi, R. and Ali Abdelkareem, M. (2023) Recent Progress in Renewable Energy Based-Desalination in the Middle East and North Africa MENA Region. *Journal of Advanced Research*, **48**, 125-156. https://doi.org/10.1016/j.jare.2022.08.016

[113] (2019) Public-Private Partnerships in California. http://www.bayareaeconomy.org/files/pdf/P3inCaliforniaWeb.pdf

[114] (2013) Water Replenishment District of Southern California Groundwater Basins Master Plan Program EIR. Scoping Report. https://www.wrd.org/files/939a56463/Draft+Program+Environmental+Impact+Report+Appendices%2C+2015.pdf

[115] Pub, Singapore's National Water Agency (2020) Smart Water Management—The Singapore's Experience. https://events.development.asia/system/files/materials/2020/11/202011-smart-water-management-singapore-experience.pdf

[116] Bai, Y., Shan, F., Zhu, Y., Xu, J., Wu, Y., Luo, X., *et al.* (2020) Long-Term Performance and Economic Evaluation of Full-Scale MF and RO Process—A Case Study of the Changi Newater Project Phase 2 in Singapore. *Water Cycle*, **1**, 128-135. https://doi.org/10.1016/j.watcyc.2020.09.001

[117] Singapore's National Water Agency (2018) Our Water, Our Future. https://www.pub.gov.sg/-/media/Images/Feature/Home/Resources/Publications/PUBOurWaterOurFuture.pdf

[118] Potyka, J., Dalibard, A. and Tovar, G. (2024) Energetic Analysis and Economic Viability of Active Atmospheric Water Generation Technologies. *Discover Applied Sciences*, **6**, Article No. 153. https://doi.org/10.1007/s42452-024-05746-z

[119] Wang, K., Yuan, B., Ji, G. and Wu, X. (2018) A Comprehensive Review of Geothermal Energy Extraction and Utilization in Oilfields. *Journal of Petroleum Science and Engineering*, **168**, 465-477. https://doi.org/10.1016/j.petrol.2018.05.012

[120] Sun, Z., Song, W., Zhang, H., Li, X., Xie, S. and Nie, H. (2023) Heat Extraction Evaluation of CO_2 and Water Flow through Different Fracture Networks for Enhanced Geothermal Systems. *Energies*, **17**, Article 86. https://doi.org/10.3390/en17010086

[121] Ragnarsson, A. (2021) Geothermal Development in Iceland 2015-2019. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01063.pdf

[122] Boguniewicz-Zabłocka, J., Łukasiewicz, E. and Guida, D. (2019) Analysis of the Sustainable Use of Geothermal Waters and Future Development Possibilities—A Case Study from the Opole Region, Poland. *Sustainability*, **11**, Article 6730. https://doi.org/10.3390/su11236730

[123] Liu, Z., Ma, Z., Wang, X., Ye, D., Yu, H. and Xin, J.H. (2022) Ultrathin Graphene Oxide Membrane for Pilot Scale Dyehouse Effluent Treatment. *Desalination*, **537**, Article ID: 115876. https://doi.org/10.1016/j.desal.2022.115876

[124] Azarafza, A., Islam, M.A., Golpazirsorkheh, Y., Efteghar, I., Sadrzadeh, M., Kamkar, M., *et al.* (2023) Aquaporin-Based Biomimetic Membranes for Low Energy Water Desalination and Separation Applications. *Advanced Functional Materials*, **33**, Article ID: 2213326. https://doi.org/10.1002/adfm.202213326

[125] (2022) Strengthening the Resilience of Urban Communities: Our Way forward. The International Federation of Red Cross and Red Crescent Societies. https://rcrcconference.org/app/uploads/2022/05/11_CoD-22-urban-resilience-back

ground-document-FINAL-EN.pdf

[126] California Department of Water Resources (2020) California Water Plan. https://www.californiawaterviews.com/california-focuses-on-water-supply-resiliency-in-updated-water-plan

[127] Public Utilities Board (PUB), Singapore (2020) Water for All: Conserve, Value, Enjoy. https://www.pub.gov.sg/

[128] European Commission (2019) EU Water Framework Directive: A Decade of Implementation. https://commission.europa.eu/system/files/2020-04/swd_2019_0439_en.pdf

[129] Xylem Inc (2023) Annual Report 2023. https://www.xylem.com/siteassets/sustainability/2023/xylem-2023-sustainability-report.pdf

[130] (2023) Final Report. Sydney Desalination Plant Pty Ltd. https://www.ipart.nsw.gov.au/sites/default/files/cm9_documents/Final-Report-Sydney-Desalination-Plant-Pty-Ltd-Review-of-prices-to-apply-from-1-July-2023-June-2023.PDF

[131] (2021) Transforming the Future of Water Impact. Report 2021. https://www.imagineh2o.org/wp-content/uploads/2022/04/Impact-Report-2021.pdf

[132] Chu, J. (2023) Desalination System Could Produce Freshwater That Is Cheaper than Tap Water. MIT News. https://news.mit.edu/2023/desalination-system-could-produce-freshwater-cheaper-0927

[133] Onda, K. (2020) Water Data Infrastructure for Low- and Middle-Income Countries. Stanford Woods Institute for Environment. https://water.stanford.edu/sites/default/files/water_data_infrastructure_v02_web.pdf

[134] UC Berkeley Water Center (2019) Annual Report on Sustainable Practices. https://www.ucop.edu/sustainability/_files/annual-reports/sustainability_report_2019_final.pdf

[135] Bordes, J.L.M. (2021) Le Programme Hydrologique Intergouvernemental. Water Sciences and Education for the Sustainable Management of Water Resources. https://www.oat.cat/Oat/wp-content/uploads/2020/05/Presentacion_UNESCO_PHI_Jose_Luis_Martin.pdf

[136] (2021) Border 2025: United States—Mexico Environmental Program. Message from the National Coordinators, EPA-906-B-21-001. https://www.epa.gov/sites/default/files/2021-05/documents/final_us_mx_border_2025_final_may_6.pdf

[137] Global Water Research Coalition (2022) Effect Based Monitoring in Water Safety Planning. https://globalwaterresearchcoalition.net/wp-content/uploads/2023/05/20200614_GWRC-WP5.3-and-5.4-Report-1.pdf

[138] Masson-Delmotte, V., *et al.* (2021) IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1-16. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FrontMatter.pdf

[139] Watson, S.M., Rob Westaway, R. and Falcone, G. (2019) A Review of Deep Geothermal Energy and Future Opportunities in the UK. European Geothermal Con-

gress. https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/158.pdf

[140] Lu, W., Ong, W.L. and Ho, G.W. (2023) Advances in Harvesting Water and Energy from Ubiquitous Atmospheric Moisture. *Journal of Materials Chemistry A*, **11**, 12456-12481. https://doi.org/10.1039/d2ta09552a

[141] Dai, Y., Liu, M., Li, J., Kang, N., Ahmed, A., Zong, Y., *et al.* (2022) Graphene-Based Membranes for Water Desalination: A Literature Review and Content Analysis. *Polymers*, **14**, Article 4246. https://doi.org/10.3390/polym14194246

[142] Fathieh, F., Kalmutzki, M.J., Kapustin, E.A., Waller, P.J., Yang, J. and Yaghi, O.M. (2018) Practical Water Production from Desert Air. *Science Advances*, **4**, eaat3198. https://doi.org/10.1126/sciadv.aat3198

[143] Dezfooli, D., Bolson, J., Arabi, M., Sukop, M.C., Wiersema, I. and Millonig, S. (2023) A Qualitative Approach to Understand Transitions toward One Water in Urban Areas across North America. *Water*, **15**, Article 2499. https://doi.org/10.3390/w15142499

[144] Alezi, D., Li, R., Alsadun, N., Malik, A., Shekhah, O., Wang, P., *et al.* (2024) Metal-Organic Framework-Based Atmospheric Water Harvesting for Enhanced Photovoltaic Efficiency and Sustainability. *Materials Advances*, **5**, 4660-4667. https://doi.org/10.1039/d3ma00960b

[145] Tiwary, S.K., Singh, M., Chavan, S.V. and Karim, A. (2024) Graphene Oxide-Based Membranes for Water Desalination and Purification. *NPJ 2D Materials and Applications*, **8**, Article No. 27. https://doi.org/10.1038/s41699-024-00462-z

[146] Alkaisi, A., Mossad, R. and Sharifian-Barforoush, A. (2017) A Review of the Water Desalination Systems Integrated with Renewable Energy. *Energy Procedia*, **110**, 268-274. https://doi.org/10.1016/j.egypro.2017.03.138

[147] United Nations (2020) The Sustainable Development Goals Report: 2020. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf