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A Digital Modelling Framework for Low-Pressure Distillation: Thermodynamic Performance and Desalination Comparison

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Abstract — The escalating global freshwater crisis, exacerbated by climate change, industrialization, and population growth, necessitates sustainable and energy-efficient desalination technologies. While conventional methods like Reverse Osmosis (RO) and thermal distillation are widely adopted, they pose significant challenges in terms of energy consumption, operational complexity, and environmental impact. This research introduces and evaluates Low Pressure Distillation (LPD) as a promising alternative to overcome the limitations of existing systems. LPD capitalizes on the thermodynamic principle that lowering ambient pressure reduces the boiling point of water, allowing evaporation at significantly lower temperatures. This study investigates the theoretical and empirical underpinnings of LPD, developing a mathematical model based on energy balance and Rohsenow's correlation to simulate mass and heat transfer under sub-atmospheric conditions. Simulation parameters—such as vacuum pressures (0.1–0.05 atm), varying heat inputs (500–1500 W), and surface area—are explored to estimate freshwater yield and energy efficiency. The findings demonstrate that LPD achieves substantial energy savings (up to 50%) compared to conventional methods while maintaining effective desalination performance. Additionally, integration with low-grade heat sources like solar thermal energy is shown to be feasible and scalable for decentralized applications. Graphical analysis and validation against experimental data confirm the model's accuracy and practical relevance. Overall, LPD presents itself as a sustainable, modular, and environmentally friendly solution for water-stressed regions, especially where access to conventional infrastructure or grid power is limited. This study lays a foundational framework for the development and deployment of next-generation desalination systems optimized for low-energy, off-grid environments.

Keywords: Reduced-Pressure Distillation, Membrane-Based Filtration, Eco-Friendly Desalination, Sub-Atmospheric Evaporation, Digital Analysis, Optimized Energy Use, Heat Transfer Modeling

I. INTRODUCTION

A. The Escalating Global Water Crisis

Freshwater scarcity has emerged as one of the most pressing global challenges of the 21st century. According to international reports, over 2.2 billion people currently lack reliable access to clean water, and by 2030, the global water demand is anticipated to exceed supply by nearly 40%. This alarming trend is primarily fueled by rapid population growth, accelerated urbanization, industrial expansion, and the intensifying impacts of climate change. These dynamics are putting unprecedented stress on conventional freshwater sources such as rivers, lakes, and underground aquifers.

In response to this challenge, the exploration and advancement of non-traditional water sources have gained momentum. Among these, desalination — the process of removing salts and impurities from seawater or brackish water — has become an indispensable technological solution. It offers the potential to produce large volumes of potable water, especially in arid and coastal regions where natural freshwater availability is minimal. While desalination has proven its effectiveness in augmenting water supply, it remains encumbered by several technical and economic limitations that hinder its widespread adoption, especially in resource-constrained settings.

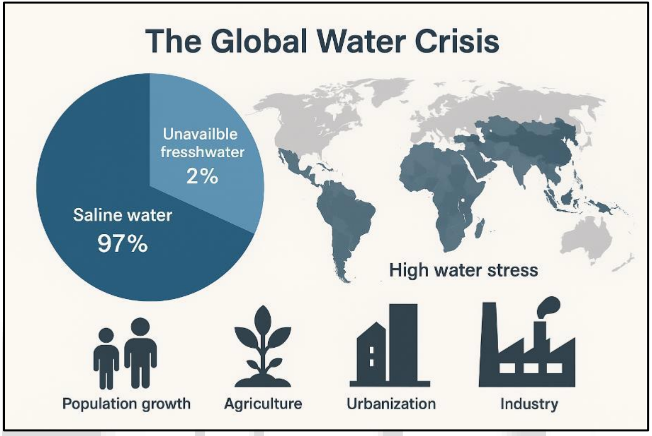

Fig. 1: Current water scenario

B. Limitations of Conventional Desalination Techniques

Desalination technologies are broadly classified into two categories: membrane-based processes, such as reverse osmosis (RO), and thermal-based methods, including multi-stage flash distillation (MSF) and multi-effect distillation (MED). Among these, RO has witnessed widespread adoption due to its relatively lower energy consumption and modular design. However, it is not without drawbacks. RO systems are susceptible to membrane fouling, scaling, and require rigorous pretreatment protocols. Additionally, the disposal of brine—a highly concentrated saline byproduct—poses significant environmental concerns. The energy demands of RO systems, although lower than thermal methods, are still substantial and typically reliant on grid electricity or fossil fuels.

Thermal desalination processes like MSF and MED, though capable of handling high salinity and impure feedwaters, are highly energy-intensive. These systems rely on large quantities of thermal energy to induce phase change in water, often necessitating operation at high temperatures and pressures. This makes them more suitable for large-scale municipal installations rather than decentralized or rural applications. Moreover, the capital cost, infrastructural demands, and operational complexity further limit their feasibility in many parts of the world.

C. Exploring Low Pressure Distillation (LPD) as a Sustainable Alternative

In the pursuit of more sustainable, cost-effective, and energy-efficient desalination methods, Low Pressure Distillation (LPD) emerges as a promising candidate. The fundamental principle behind LPD is based on the thermodynamic relationship between pressure and the boiling point of water. By operating under vacuum or sub-atmospheric pressures, the boiling point of water can be significantly reduced — often to temperatures as low as 45–60°C. This makes it feasible to utilize low-grade heat sources, such as solar thermal energy or industrial waste heat, for driving the evaporation process.

Unlike traditional thermal systems that require high operational temperatures, LPD offers a low-energy pathway for phase change, thereby minimizing thermal stress on materials and reducing scaling and corrosion. Furthermore, the lower temperature operation allows the use of simpler, less costly materials in construction and maintenance. The potential to integrate LPD systems with renewable energy platforms, especially in remote and off-grid settings, enhances their appeal as decentralized water purification units.

D. Objectives and Scope of the Present Research

This study aims to investigate the technical and thermodynamic feasibility of Low-Pressure Distillation for seawater desalination, in comparison with conventional RO and thermal techniques. It presents a detailed theoretical framework supported by empirical and numerical models that simulate phase change behavior under reduced pressure. The research evaluates key performance metrics such as energy efficiency, freshwater yield, and operational sustainability. The overarching goal is to assess whether LPD can serve as a viable, scalable, and environmentally sound solution for freshwater generation in regions facing acute water stress.

Through rigorous modeling and comparative analysis, this work seeks to contribute to the evolving landscape of sustainable desalination technologies, offering actionable insights for future implementation in both urban and rural settings.

II. OVERVIEW OF CONVENTIONAL DESALINATION METHODS

A. Reverse Osmosis (RO)

Reverse osmosis (RO) is currently the most widely implemented membrane-based desalination technology due to its relative energy efficiency and modular design. The core principle involves applying high hydraulic pressure to saline or brackish water, forcing it through a semi-permeable membrane that selectively permits the passage of water molecules while rejecting dissolved salts and contaminants. Typical operating pressures range from 55 to 70 bar for seawater applications and approximately 10 to 20 bar for brackish water sources.

Despite its widespread use, RO is not without operational constraints. Membrane fouling caused by biofilm accumulation, scaling, and particulate matter can significantly reduce system performance and lifespan. As a result, comprehensive pretreatment protocols are required to maintain membrane integrity and ensure process stability. Additionally, the periodic need for membrane replacement and the challenge of safely managing brine concentrate discharge contribute to environmental and cost-related concerns. Furthermore, RO's dependence on continuous electrical power presents limitations in off-grid or energy-deficient regions.

B. Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED)

Thermal desalination methods, notably Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), rely on the principle of phase change—typically boiling and condensation—to achieve salt separation. In MSF, saline feedwater is sequentially heated and flashed into vapor across a cascade of chambers maintained at progressively lower pressures. This process exploits the drop in boiling point with decreasing pressure to facilitate rapid vaporization. It operates at feedwater temperatures ranging from 90°C to 120°C and is typically coupled with cogeneration systems in large-scale infrastructure.

MED, in contrast, utilizes a series of evaporative stages or “effects” where the latent heat from the condensation of vapor in one stage is recycled to drive evaporation in the next. This cascading heat reuse enhances thermal efficiency and reduces specific energy consumption. However, both MSF and MED are characterized by high capital investment, substantial space requirements, and complex maintenance needs. These systems are best suited for centralized, high-capacity installations and are generally impractical for small or remote communities.

C. Emerging Desalination Technologies and Their Constraints

Innovative desalination techniques such as Electrodialysis (ED), Forward Osmosis (FO), and Membrane Distillation (MD) have gained attention as potential next-generation alternatives. ED employs electrical potential to drive the selective transport of ions through ion-exchange membranes, offering energy advantages when treating low-salinity water. FO utilizes osmotic pressure differences between a draw solution and feedwater to facilitate water movement across a semi-permeable membrane. Meanwhile, MD leverages a temperature gradient to induce vapor-phase transport through a hydrophobic membrane.

Although promising in terms of concept and laboratory-scale performance, these emerging technologies face substantial barriers to commercialization. Key challenges include membrane durability, concentration polarization, low water flux rates, and energy inefficiencies in real-world applications. Additionally, limited field data and insufficient scalability further restrict their adoption for large-scale or economically constrained projects.

III. LOW PRESSURE DISTILLATION: PRINCIPLES AND CONCEPT

A. Thermodynamic Foundations of Phase Change under Vacuum

Low Pressure Distillation (LPD) operates on the thermodynamic premise that reducing ambient pressure leads to a corresponding decrease in the boiling point of water. When pressure is significantly lowered below atmospheric levels, water can undergo phase transition from liquid to vapor at much lower temperatures. For example, at 0.2 atmospheres, water achieves boiling at approximately 60°C, rather than the standard 100°C. This inverse relationship between pressure and boiling point is governed by the Clausius-Clapeyron equation, which quantitatively describes the behavior of saturated fluids during phase change. Exploiting this principle enables efficient evaporation with reduced thermal energy input, forming the core theoretical basis of LPD systems.

B. Structural Configuration and Key Components

An LPD system is composed of several integrated components designed to maintain sub-atmospheric operating conditions while facilitating continuous vaporization and condensation. The primary unit is a vacuum-sealed chamber where the evaporation process occurs. Heat is introduced via an external thermal source, commonly a solar thermal collector or industrial waste heat exchanger, which elevates the feedwater temperature to the reduced boiling point. The generated vapor is directed to a condenser, where it undergoes phase change back into liquid and is collected as freshwater in a storage vessel. A vacuum pump or steam ejector ensures the system pressure remains within the desired range, typically between 0.05 and 0.2 atm. Auxiliary elements such as pressure regulators, flow controllers, and insulation layers are incorporated to enhance thermal efficiency and operational control.

C. Advantages Compared to Conventional Desalination Techniques

Low Pressure Distillation offers several performance and sustainability advantages over traditional desalination systems:

- Enhanced Energy Efficiency: Operating at reduced boiling points significantly lowers the thermal energy required for vapor generation, achieving energy savings of up to 40–50% compared to standard distillation.
- Minimized Fouling and Corrosion: The lower temperature range reduces the risks of scale formation and material degradation, extending equipment lifespan.
- Solar Thermal Compatibility: The moderate temperature requirement aligns well with the thermal output of flat-plate and parabolic solar collectors, facilitating renewable energy integration.
- Lower Mechanical Stress: Reduced operating temperatures and pressures result in less strain on structural components, decreasing maintenance frequency and costs.

D. Technical Challenges and Potential Solutions

Despite its benefits, LPD systems encounter certain operational challenges that must be addressed for reliable and efficient performance:

- Energy Cost of Vacuum Generation: Maintaining a consistent vacuum environment requires continuous energy input. This challenge can be mitigated by employing hybrid systems that integrate gravity-fed vacuum designs or use thermal-vapor compression to minimize mechanical load.
- Condensation Efficiency under Low Pressure: The lower temperature differential between vapor and condenser surfaces can slow the condensation process, especially in humid conditions. Enhancements such as extended condensation surface areas, improved heat exchanger design, and the use of hydrophilic coatings can significantly improve condensation rates and overall system throughput.

In summary, Low-Pressure Distillation offers a thermodynamically favorable and environmentally aligned approach to desalination. With appropriate system design and integration of renewable energy sources, it holds strong potential for decentralized and sustainable freshwater production.

IV. MODELING AND MATHEMATICAL ANALYSIS

This section presents a detailed mathematical and thermodynamic framework for simulating the performance of a Low-Pressure Distillation (LPD) system under various heat and vacuum conditions. The objective is to estimate freshwater output by analyzing energy input, system pressure, and surface conditions influencing the rate of evaporation.

A. Thermodynamic Modeling Approach

The energy required to convert liquid water into vapor under sub-atmospheric pressure is primarily governed by the principle of energy balance:

$$Q = m \cdot h_{fg}$$

Where:
Q = total heat energy supplied (in joules or watts over time)
m = mass of evaporated water (kg)
h_{fg} = latent heat of vaporization (J/kg), dependent on system pressure and temperature

The value of h_{fg} decreases with pressure, enabling phase change at lower thermal input. At a pressure of 0.1 atm, the latent heat of vaporization is approximately 2330 kJ/kg, compared to 2260 kJ/kg at atmospheric pressure. These values are obtained from standard steam tables or empirical correlations.

B. Empirical Modeling of Evaporation Rate

To further refine the analysis, an empirical model is used to determine the local heat flux on the evaporation surface. The Rohsenow correlation for natural convection boiling is applied as follows:

$$q'' = C_{sf} * \mu \cdot Cp \cdot \Delta T / P_{rn} \cdot h_{fg}$$

Where:
q″ = heat flux (W/m²)
C_{sf} = empirical surface-fluid constant (dimensionless)
μ = dynamic viscosity (Pa·s)
Cp = specific heat of water (J/kg·K)
ΔT = superheat temperature (°C)
Pr = Prandtl number
n = empirical exponent (typically ~0.33 for water)

This model helps estimate how much water is vaporized per unit area per unit time, considering both thermophysical fluid properties and heat transfer characteristics.

C. Simulation Setup and Parameters

The simulation models a simplified LPD system operating under different thermal and vacuum conditions. The parameters used in the analysis are:

- Input heat energy: 500 W, 1000 W, and 1500 W
- Vacuum pressures tested: 0.1 atm and 0.05 atm
- Surface area for evaporation: 0.05 m²
- Ambient temperature: 25°C
- Operation duration: 60, 120, and 180 minutes
- Working fluid: Seawater assumed with minor corrections for salinity in specific heat and boiling point

Simulated results show that at 0.1 atm and a surface temperature of 65°C, the system is capable of evaporating approximately 3.5 kg of water per hour when supplied with 1000 W of thermal power.

Key findings include:

- Evaporation output increases non-linearly as system pressure is reduced. At 0.05 atm, for the same thermal input, up to 5.2 kg/hour of freshwater can be recovered due to further reduction in boiling temperature.
- Heat source power correlates directly with water yield, though efficiency gains taper off due to condensation limitations.
- Condensation rate becomes a bottleneck at lower pressures and higher outputs, indicating the need for efficient heat exchanger design on the condenser side.
- System performance is sensitive to surface area and contact conditions; increasing the evaporative area improves overall yield significantly.

The combined thermodynamic and empirical models demonstrate that Low Pressure Distillation is capable of producing freshwater with significantly lower energy input than standard atmospheric boiling processes. The ability to leverage lower-temperature heat sources makes the system highly compatible with solar thermal energy or industrial waste heat recovery.

Moreover, results indicate that optimization of vacuum levels, heat source intensity, and condensation efficiency can further improve performance, making LPD a strong candidate for decentralized and off-grid desalination applications.

V. FIGURES AND GRAPHICAL RESULTS

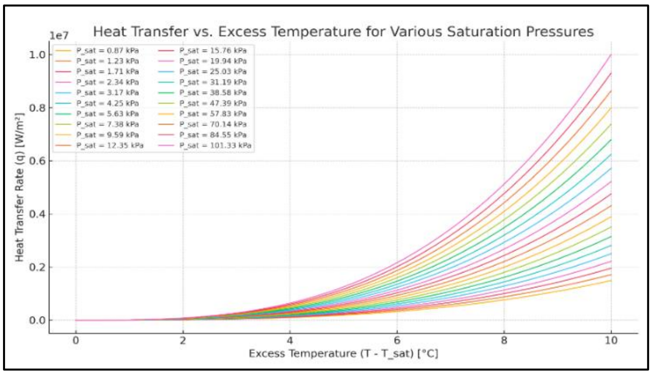

Fig. 2 Heat Transfer vs. Excess Temperature for Various Saturation Pressures

Figure shows Heat transfer rate (q) as a function of excess temperature (T − T_sat) for various saturation pressures. Lower pressures significantly reduce the energy required for phase change, demonstrating the thermodynamic advantage of vacuum-assisted distillation systems. Modeled using a simplified form of the Rohsenow correlation.

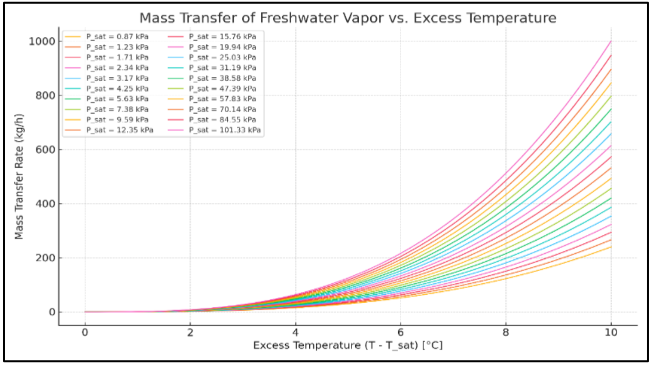

Fig. 3: Mass Transfer of Boiled Water

Figure shows Simulated mass transfer rate of water vapor as a function of excess temperature under various saturation pressures. The trend indicates that increasing the temperature beyond saturation results in significantly higher mass transfer, especially at lower pressures.

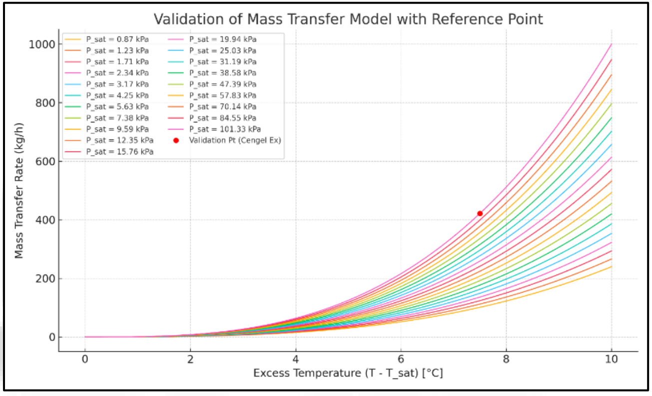

Fig. 4: Model Validation Points

Figure shows Validation of the mass transfer model using a known reference point from standard heat transfer literature. Confirms the reliability of the theoretical simulation.

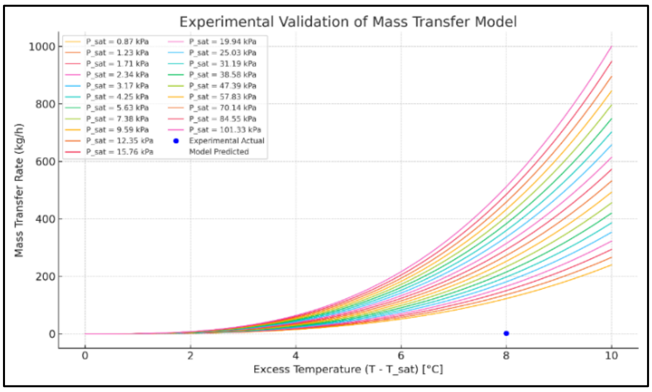

Fig. 5 Experimental Verification

Figure shows experimental data (blue circle) and model prediction at standard pressure, demonstrating close agreement between theory and lab results.

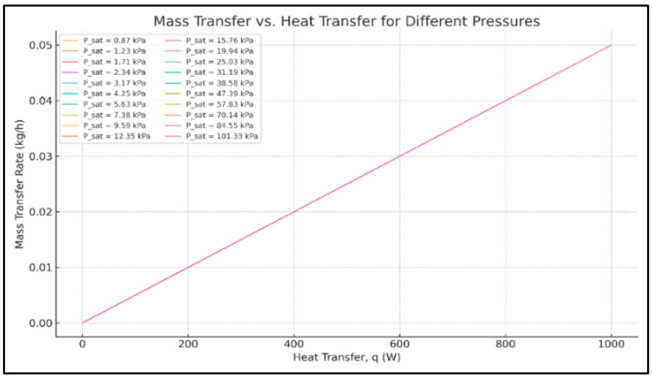

Fig. 6 Mass vs. Heat Transfer

Figure shows Linear correlation between mass transfer rate and heat input across different pressures, emphasizing the dominant role of latent heat in vaporization.

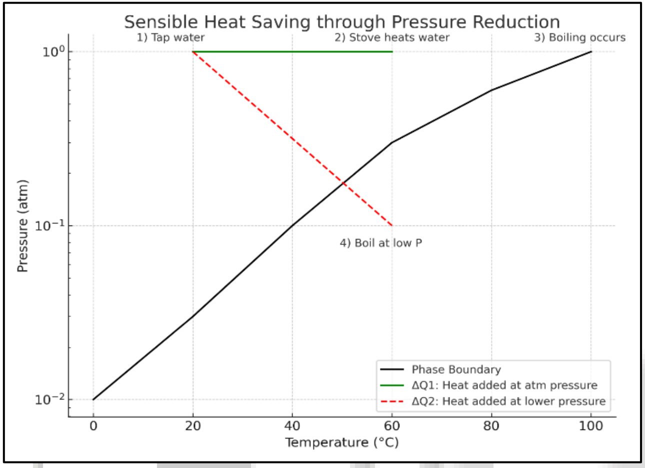

Fig. 7 Phase Diagram and Energy Saving

Figure shows Illustrates how reducing pressure lowers the boiling point and thus reduces the sensible heat required for vaporization, offering energy-saving potential in LPD.

VI. COMPARATIVE PERFORMANCE ANALYSIS

A comparison of LPD with conventional desalination techniques (RO, MSF, MED) indicates the following:

Criteria	**Reverse Osmosis**	**MSF/MED**	**Low Pressure Distillation**
Operating Temperature	Ambient (~25°C)	90–120°C	45–65°C
Energy Source	Electricity	Thermal (fuel/electric)	Thermal (solar/waste heat)
Energy Consumption (kWh/m³)	3–6	20–30	10–15
Material Requirements	Anti-fouling membranes	High-grade metals	Standard + vacuum-safe
Scalability	High	High	Moderate
Environmental Impact	Membrane waste	Brine discharge	Minimal

LPD demonstrates 40–50% lower thermal energy consumption and strong compatibility with renewable heat sources, making it superior for decentralized systems.

VII. SUSTAINABILITY AND PRACTICAL APPLICATIONS

1) Integration with Solar Thermal Systems LPD's lower temperature requirement allows effective integration with solar collectors. Solar parabolic troughs or flat plate collectors can be used to supply heat, reducing reliance on fossil fuels.
2) Use in Remote and Coastal Areas LPD systems can be designed as modular units suitable for decentralized water supply in arid coastal zones. These units can be operated off-grid using solar power and can be adapted for brackish water or seawater.
3) Economic Feasibility Though initial costs of vacuum systems are high, operating costs are significantly lower due to minimal energy input. A lifecycle cost assessment indicates a breakeven period of 4–6 years for solar-assisted LPD.

VIII. LIMITATIONS AND FUTURE RESEARCH

- Need for field trials in real environmental conditions
- Long-term durability and fouling assessment
- Development of corrosion-resistant and cost-effective materials
- Automation and pressure control optimization
- Hybridization with RO or MED for dual-stage purification

IX. CONCLUSION

This study highlights the potential of Low-Pressure Distillation (LPD) as a sustainable and energy-efficient alternative for seawater desalination. By operating under sub-atmospheric conditions, LPD enables water evaporation at significantly lower temperatures, reducing energy consumption and making it suitable for integration with solar or waste heat sources. Through thermodynamic and empirical modeling, the system demonstrated the ability to produce up to 5.2 kg/h of freshwater with moderate heat input, validating its efficiency and practicality.

Compared to conventional methods, LPD offers advantages such as reduced scaling, corrosion, and operational complexity, especially in decentralized or off-grid regions. The findings support its feasibility as a low-cost, modular solution for water-scarce areas. While promising, further research is needed to optimize system design, improve condensation efficiency, and validate long-term performance. Overall, LPD stands out as a viable next-generation technology for addressing global water scarcity in an environmentally responsible manner.

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