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Solar-Aqua Sphere: A Multifunctional Solar-Powered Device for Water Generation, Purification, and Aquatic Ecosystem Support

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KEYWORDS

Ustainability;
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ABSTRACT

Water scarcity and sustainable water management remain critical issues for Hong Kong and the Greater Bay Area, intensified by rapid urbanization and increasingly variable climate conditions. Existing measures such as shade balls and conventional atmospheric water generation (AWG) systems tend to solve isolated problems and rarely integrate water quality, ecosystem support, or environmental monitoring. This study presents the Solar-Aqua Sphere, a multifunctional, solar-powered device that produces potable water from ambient air, sterilizes it with UV-C, and supports aquatic micro-ecosystems within a modular, sensor-enabled platform. The system combines a thermoelectric AWG module, a UV-C purification chamber, and an aquatic compartment managed through real-time sensing and data logging. Laboratory tests assessed the AWG module under controlled temperature and humidity, demonstrating effective heat exchange and condensation. While the prototype's water output was constrained by surface area and passive cooling limits, results confirm the feasibility of the core design and point to improvements such as stronger cooling capacity and expanded condenser surfaces. Offering an integrated approach to water generation, purification, and ecological resilience, the Solar-Aqua Sphere shows strong potential for application in urban reservoirs and resource-constrained settings in Hong Kong and beyond.

INTRODUCTION

Hong Kong and the surrounding Greater Bay Area have long grappled with the challenges of water scarcity and sustainable water management. These issues have been exacerbated by rapid urbanization and the growing unpredictability of regional climate patterns [1]. As of 2023, Hong Kong imports the majority of its potable water from the Dongjiang River in Guangdong Province, a dependence that leaves the city vulnerable to supply disruptions and regional competition for re-

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sources [2]. Local reservoirs, which supplement imported water, are themselves subject to high evaporation rates—particularly during the hot, humid summers that define the region. Expected shifts in climate, including more frequent droughts and extreme weather events, are likely to intensify these pressures and further disrupt traditional water cycles and infrastructure [4].

In recent years, a variety of technological approaches have emerged to mitigate these challenges. For example, shade balls—black plastic spheres that float atop reservoirs—are now used to reduce evaporation by limiting surface exposure to sunlight. Atmospheric water generation (AWG) devices, which condense water vapor from the air using solar or other renewable energy sources, have also shown promise [5]. However, most such solutions address only a single aspect of the water crisis, such as evaporation or supply, and rarely incorporate broader concerns like water quality, ecosystem health, or integrated environmental monitoring.

Water quality in Hong Kong's reservoirs and ponds remains a persistent issue, as bacterial contamination and harmful algal blooms can threaten both ecological integrity and public health [3]. While UV-based water sterilization offers a reliable, chemical-free method for inhibiting bacterial growth, it is rarely implemented at the scale of reservoirs. At the same time, the preservation of local aquatic ecosystems is essential for maintaining biodiversity and long-term resilience—yet is often overlooked in engineering-focused solutions.

This study introduces the Solar-Aqua Sphere: a novel, multifunctional, solar-powered device specifically designed for the climatic and urban conditions of Hong Kong and the Greater Bay Area. Unlike conventional shade balls or standalone AWG systems, the Solar-Aqua Sphere uniquely integrates air-to-water condensation, UV sterilization, and a micro-ecosystem within a single, modular unit. It is also equipped with a suite of environmental sensors and a microcontroller, enabling real-time data collection on temperature, humidity, light levels, and water quality. These features support both research and adaptive management. By bridging the gap between water conservation, quality assurance, and ecosystem support, the Solar-Aqua Sphere directly contributes to multiple United Nations Sustainable Development Goals. It promotes SDG 6 (Clean Water and Sanitation) by increasing local water availability and ensuring water safety; supports SDG 11 (Sustainable Cities and Communities) through urban ecological integration; and advances SDG 13 (Climate Action) by leveraging renewable energy and improving resilience to climate-related water risks. This paper presents the device's design rationale, laboratory testing results, and discusses its potential to enhance water security, biodiversity, and sustainable development in Hong Kong and beyond.

The rest of the paper is organized as follows: Section 2 presents the literature review of the applications and technologies of the Shade Ball and Atmospheric Water Generation (AWG). Section 3 introduces the design of the Solar-Aqua Sphere and its functional modules. Section 4 presents the experiment of the Atmospheric Water Generation (AWG) System and analyzes its performance. Section 5 interprets the experimental results about objectives, compares the device's performance to relevant technologies, addresses limitations, and suggests future directions. Section 6 concludes the paper.

LITERATURE REVIEW

Shade Balls: Evaporation Control and Limitations

Shade balls, also known as floating covers or conservation balls, have emerged as a practical solution for reducing evaporation from open water reservoirs, particularly in regions experiencing high temperatures and intense solar radiation (**Figure 1)**. The concept involves deploying thousands of hollow, black plastic spheres that form a mobile layer on the water surface, thereby reducing the amount of sunlight that directly contacts the water [6]. Field studies, including those conducted in both California and Hong Kong, have demonstrated that shade balls can reduce evaporation losses by up to 90% under optimal conditions. The mechanism is twofold: the balls physically block the transfer of heat and UV radiation into the water, and they also reduce wind-driven evaporation by damping surface turbulence [6].

Despite their effectiveness, shade balls present several limitations. First, they do not address water quality concerns such as microbial contamination, chemical pollutants, or algal blooms. Second, their large-scale deployment requires significant initial investment, ongoing maintenance, and eventual disposal or recycling of the plastic spheres. Additionally, shade balls may impact aquatic ecosystems by altering light penetration

Figure 1 | Deployment of shade balls at the LA Reservoir[7]

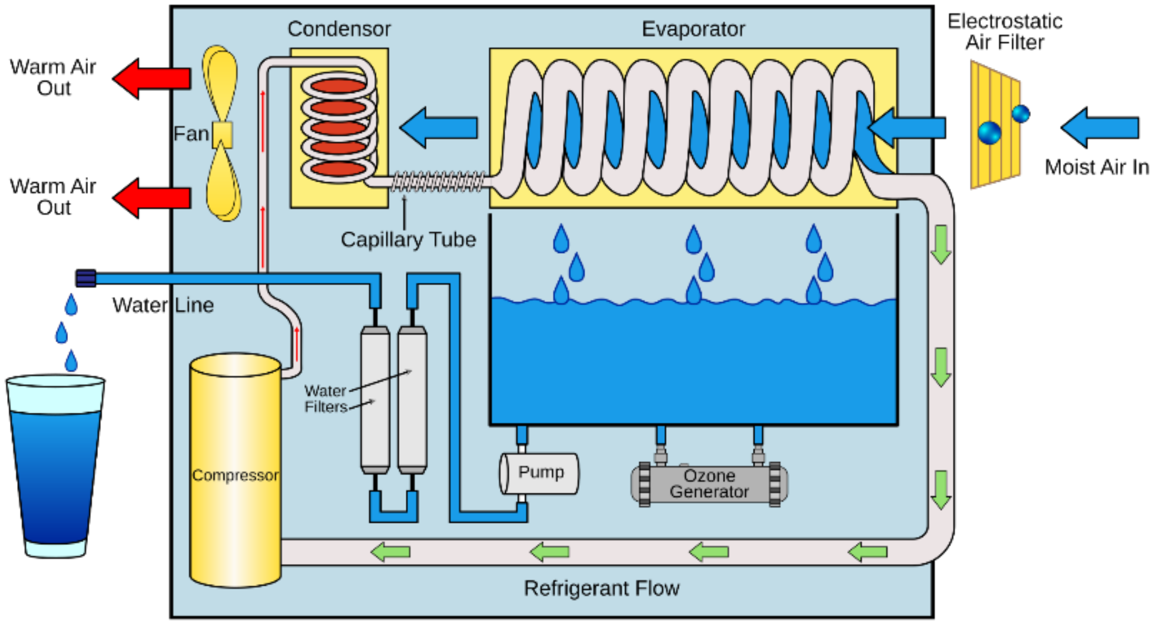

Figure 2 | Example of cooling-condensation process[9]

and gas exchange at the water surface [8]. Recent studies have also raised questions about the potential leaching of plastic additives into the water over time, although evidence remains inconclusive.

Atmospheric Water Generation (AWG): Principles and Applications

Atmospheric water generation (AWG) is an emerging technology that leverages the humidity present in ambient air to produce potable water **(Figure 2)**. AWG devices typically function by cooling air to below its dew point, causing water vapor to condense on specialized surfaces. Solar-powered AWG systems are particularly attractive for off-grid or resource-limited settings, as they combine renewable energy with decentralized water production [5]. Advances in thermoelectric materials, heat exchangers, and energy-efficient compressors have improved the performance and feasibility of AWG systems in recent years. The application of AWG has been especially prominent in arid and semi-arid environments, where conventional freshwater sources are scarce but atmospheric humidity may still be sufficient for water extraction [5]. Research has demonstrated that modern AWG units can achieve daily yields in the range of several liters per square meter, depending on local humidity, temperature, and device design.

However, AWG technology also faces notable constraints. Its efficiency drops significantly in low-humidity conditions, and the energy requirements for air cooling can be substantial, particularly for larger-scale installations. Moreover, most AWG devices focus solely on water production and do not incorporate integrated purification or real-time water quality monitoring. This limits their applicability in environments where air or condensed water may contain pollutants, or where ecosystem integration is desirable.

Integration Gaps and Research Directions

Both shade balls and AWG devices represent important engineering responses to water scarcity, yet each addresses only a subset of the broader water management challenge. Shade balls are primarily designed to reduce evaporative losses from existing water stores, but are limited in their scope regarding water quality and ecosystem health. In contrast, AWG devices offer a means of augmenting water supply but often lack features such as integrated sterilization, biodiversity support, or environmental monitoring. Few studies have explored the integration of these technologies or their extension to multifunctional, sensor-enabled platforms tailored for urban environments like Hong Kong. There is a clear research gap in developing modular solutions that combine water conservation, renewable water generation, purification, and ecological support within a single system.

DESIGN DESCRIPTION

The Solar-Aqua Sphere is a purpose-built, modular device designed to address key challenges of water scarcity, water quality, and ecological sustainability in urban reservoirs. The design is shown in **Figure 3**. The device integrates advanced atmospheric water generation (AWG) and UV sterilization technologies, along with

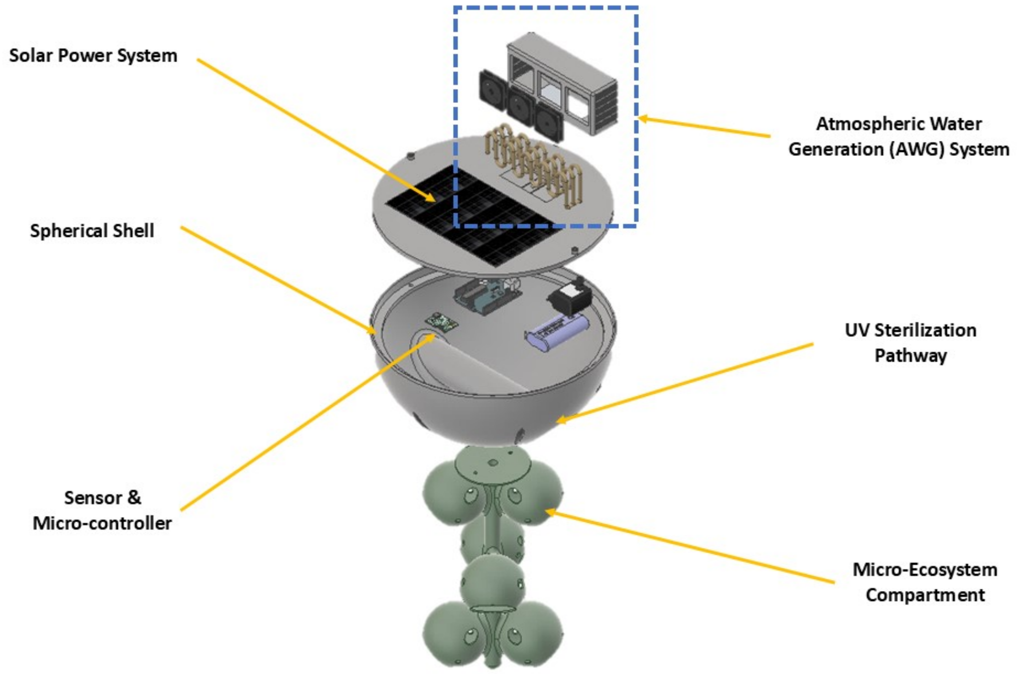

Figure 3 I Design of Solar-Aqua Sphere

real-time environmental monitoring and support for a micro-ecosystem, all within a robust, buoyant spherical structure. This section details the rationale behind the design, major structural and functional components, and the integration of various subsystems.

Structural Configuration

The main body of the Solar-Aqua Sphere is formed from a UV-resistant polycarbonate shell, 350 mm in diameter and 4 mm in wall thickness. The upper hemisphere remains transparent to facilitate light transmission. At the same time, the lower half is coated with a matte black finish to promote solar absorption and minimize algae growth inside the device. The shell is sealed with a high-grade silicone gasket and secured using stainless steel fasteners, ensuring both buoyancy and long-term water resistance.

Atmospheric Water Generation (AWG) System

The AWG system occupies the upper section of the sphere and operates on the principle of vapor condensation via thermoelectric cooling. A TEC1-12709 Peltier module is installed between an external copper heat sink, exposed to ambient air, and an internal aluminum condensation plate with a surface area of 0.05 m^2. A brushless DC fan circulates humid air across the condensation plate, optimizing the dew formation process. Condensed water droplets are directed by gravity into a food-grade, sealed reservoir located at the base of the sphere. All water-contact components are sterilizable and constructed from materials certified for potable water use.

UV Sterilization Pathway

Collected water passes through an integrated UV-C sterilization chamber before being stored or released. The chamber contains a 254 nm, 1.5W low-pressure mercury UV lamp, protected by a quartz sleeve to ensure chemical compatibility and maximum irradiation. Water is exposed to the UV lamp in a thin film, maximizing pathogen inactivation efficiency. The UV lamp is activated automatically upon detection of water flow, powered via a dedicated low-voltage circuit.

Micro-Ecosystem Compartment

A separate, sealed compartment in the lower hemisphere supports a micro-ecosystem comprising aquatic plants (such as Hydrilla verticillata) and small invertebrates or fish (e.g., Poecilia reticulata). Overflow distilled water from the AWG system replenishes this chamber, while the transparent upper shell ensures sufficient illumination for photosynthesis. The compartment enables the study of ecological interactions and long-term habitat support within the device.

Environmental Sensing and Control

An integrated ESP32 microcontroller manages the operational logic and data management of the Solar-Aqua Sphere. The device is equipped with a suite of sensors for comprehensive environmental monitoring. The sensors and their specifications are shown in **Table 1**, and the circuit diagram is shown in **Figure 4**.

Table 1 I Summary of Sensors, Modules, and Controller in the Solar-Aqua Sphere

Item	Parameter(s)	Type	Specifications	Applications
ESP 32	Device control, Data management Communication	SoC microcontroller	Dual-core, 240 MHz; Wi-Fi/ Bluetooth; 4MB flash; 32 GPIO pins	Central control of sensors, data logging, wireless transmission, and automation
DHT22	Air temperature Humidity	Digital sensor	Temp: -40–80°C, ±0.5°C; RH: 0–100%, ±2%	Monitors ambient conditions for AWG efficiency and climate data logging
DS18B20	Water temperature	Digital probe	-55–125°C, ±0.5°C	Measures temperature in AWG and ecosystem chambers
NEO-6M	Geographic location	GNSS receiver	Accuracy: <2.5 m CEP (open sky), 50 channels	Provides location data for device tracking, deployment mapping, and geo-tagging sensor data

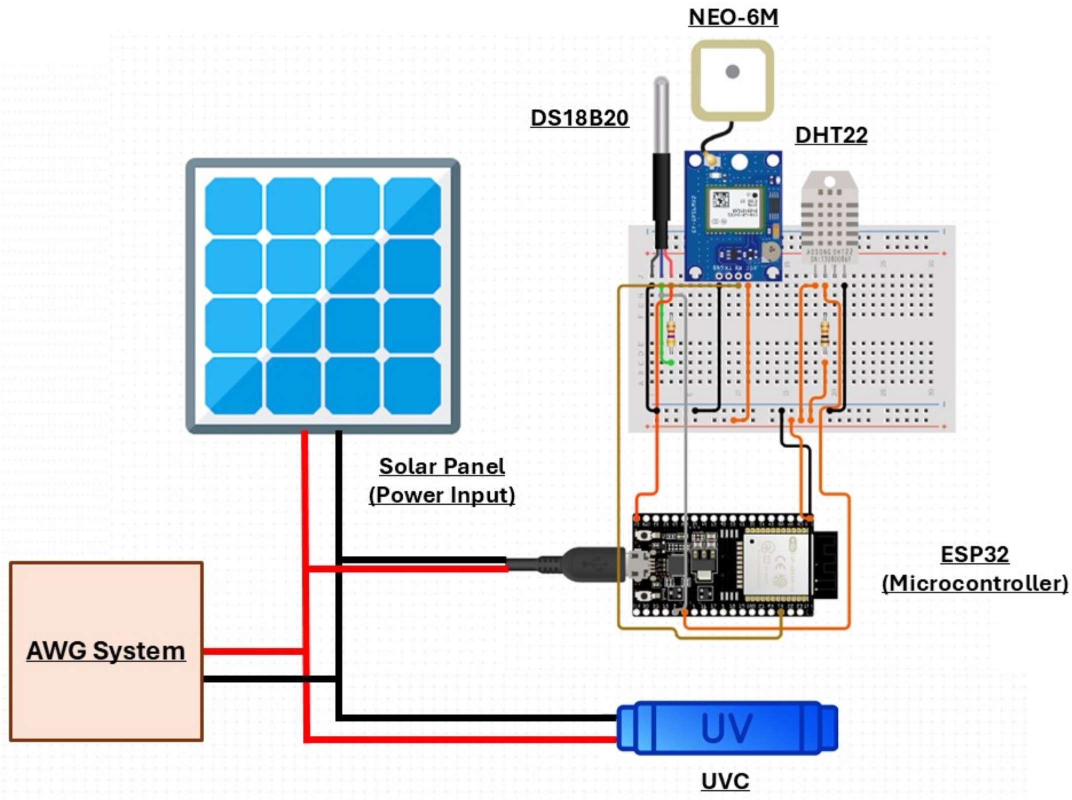

Figure 4 I Circuit diagram of the system

EXPERIMENT AND RESULTS

The feasibility of the AWG module in the Solar-Aqua Sphere was evaluated through a series of controlled experiments. A prototype of the AWG module of the Solar-Aqua Sphere is made to test the feasibility of the system, as shown in **Figure 5**. A small water pump continuously circulates the chilled water from the tank through the copper tubes. This ensures the copper tubes stay cold, maximizing condensation of atmospheric moisture on their surface. A series of hollow copper tubes is arranged vertically and connected in a loop. These tubes serve as the condensation surface where moisture from the surrounding air cools and turns into water droplets. Ice pads are placed in the water tank to lower and maintain the water temperature at around 18°C. This simulates the effect of an underwater environment, providing a cold source for the heat exchanger.

The testing environment is controlled in an air-conditioned laboratory where the room temperature is around 25°c and the humidity is around 55%.

Results

The prototype Atmospheric Water Generation (AWG) module of the Solar-Aqua Sphere was tested under controlled laboratory conditions to evaluate its

Table 2 | Water Temperature and Absorbed Energy in AWG Feasibility Experiment

Time (min)	Input Temp.	Output Temp.	ΔT	Absorbed Energy
0 – 5	21.2°c	21.0°c	-0.2°c	669 J
5 – 10	20.8°c	20.4°c	-0.4°c	1339 J
10 -15	20.0°c	19.6°c	-0.4°c	1339 J
15 – 20	19.5°c	19.0°c	-0.5°c	1674 J
20 – 25	18.9°c	18.4°c	-0.5°c	1674 J
25 – 30	18.4°c	18.0	-0.4	1339 J
30 – 35	18.1	17.6	-0.5	1674 J
35 – 40	17.8	17.7	-0.1	335 J
40 – 45	18.2	18.0	-0.2	669 J
45 – 50	19.2	18.5	-0.7	2343 J
50 – 55	19.8	19.0	-0.8	2678 J
55 – 60	20.4	19.6	-0.8	2678 J

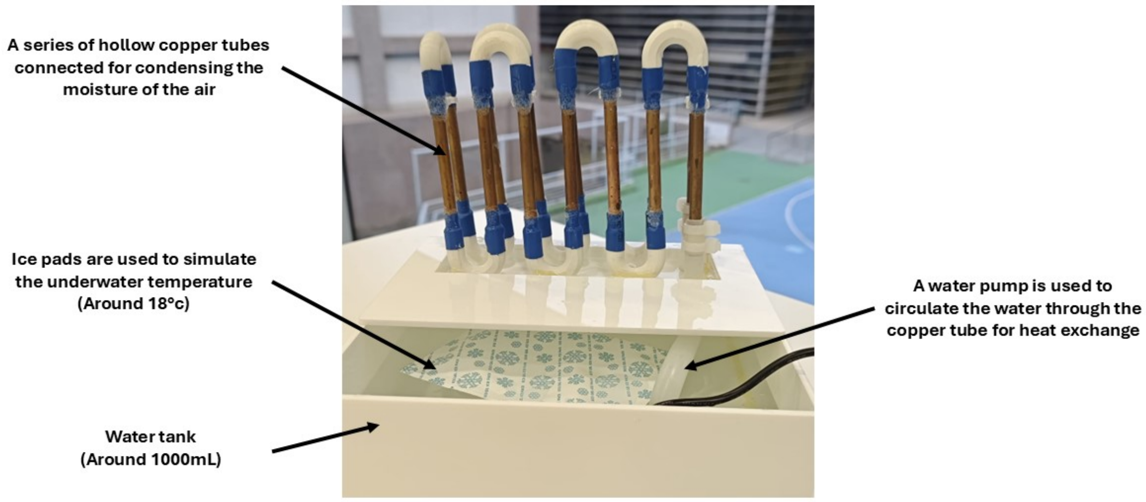

Figure 5 | Experiment setup to test the feasibility of the AWG system

heat exchange performance and condensation potential. Water temperatures at the input and output of the copper tube condenser were recorded at regular intervals during a 60-minute circulation test, and the absorbed energy was calculated for each period. **Table 2** summarizes the changes in water temperature and quantifies the heat transfer achieved by the system, providing insights into the feasibility and efficiency of the AWG module design.

DISCUSSION

The feasibility experiments conducted with the Solar-Aqua Sphere prototype demonstrated effective heat exchange and initial condensation of atmospheric water under controlled laboratory conditions. The system achieved a consistent reduction in water temperature during operation, confirming that the core AWG mechanism is functional. However, the observed water yield and heat transfer were limited by the relatively small surface area of the condenser and the passive nature of the cooling method.

Compared to conventional shade balls and standalone atmospheric water generation (AWG) devices, the Solar-Aqua Sphere offers a unique combination of water generation, UV-based purification, and micro-ecosystem support within a single modular platform. While shade balls have proven effective in reducing evaporation losses by up to 90% [6], they do not address water quality or ecosystem health. Most existing AWG systems are focused on maximizing water yield, often at the expense of energy efficiency or integration with environmental monitoring [5,8]. In this context, the Solar-Aqua Sphere represents an advancement by integrating real-time sensing, UV sterilization, and ecological support, aligning with the growing need for multifunctional urban water solutions [1,4].

Several limitations emerged during prototype testing. First, the water yield was constrained by the limited condenser surface area and passive cooling, resulting in modest condensation rates. Additionally, the reliance on ice pads for initial cooling is not sustainable for long-term or field deployment. The gradual warming of the input water over time further reduced condensation efficiency, indicating a need for active, renewable cooling sources such as thermoelectric modules powered by onboard solar panels. Furthermore, the laboratory conditions did not fully replicate the variable environmental factors present in outdoor reservoirs, such as fluctuating humidity, temperature, and wind. Future testing in real-world environments is necessary to evaluate device performance under more diverse and challenging conditions.

To enhance the practicality and effectiveness of the Solar-Aqua Sphere, several avenues for optimization are recommended:

1) Increase Condenser Surface Area: Expanding the condensation surface will directly improve water yield.
2) Integrate Active Cooling: Incorporating thermoelectric cooling modules powered by solar energy can provide more consistent and renewable cooling.
3) Optimize Airflow: An Improved airflow design may enhance heat exchange and condensation rates.
4) Field Testing: Deploying prototypes in outdoor reservoirs will provide insights into real-world performance and environmental interactions.
5) Long-term Monitoring: Continuous data collection will help refine operational parameters and understand ecological impacts over time.

CONCLUSION

This study presents the design and preliminary testing of the Solar-Aqua Sphere, a multifunctional, solar-powered device for water generation, purification, and aquatic ecosystem support. The feasibility experiment for the AWG module confirmed that the system could effectively facilitate heat exchange and initiate atmospheric water condensation using a passive, water-cooled copper tube array. Although the water yield in this prototype stage was limited by surface area and cooling method, the results validate the underlying principle and support the potential for further optimization.

Future work will focus on enhancing condensation efficiency by increasing the heat exchanger surface area, integrating active thermoelectric cooling powered by solar energy, and optimizing airflow across the condensation surfaces. Additional field testing under variable environmental conditions will also be conducted to assess performance in real-world settings. The integration of UV sterilization, real-time environmental monitoring, and micro-ecosystem support within the Solar-Aqua Sphere positions the device as a promising solution for sustainable water management and ecosystem resilience in urban reservoirs, particularly in regions such as Hong Kong and the Greater Bay Area.

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