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Smart Hybrid Drinking Water Systems Integrating Atmospheric Water Generation, Rainwater Harvesting, and Solar Energy: A Comprehensive Review

Vijay W. Bhatkar[1], Amol Yadav[2], Pankaj K. Jadhav[3], Tripti Kumbalpuri[4], Sandeep A. Adhyapak[5]

[1]Marathwada Mitra Mandal's College of Engineering, Pune, MS India
[2]JSPM's Jayawantrao Sawant College of Engineering, Pune, MS, India
[3] Ratan Tata Maharashtra State Skill University, Mumbai, MS, India
[4] Govt. College of Engineering, Nagpur, MS, India
[5]Water Field Technologies Pvt. Ltd, Thane (W) MS, India

Abstract

Climate change has further aggravated the situation by increasing the frequency and intensity of droughts, heat waves, and erratic rainfall events. The changing climatic conditions have reduced the reliability of conventional surface and groundwater resources, making decentralized and climate-resilient drinking water technologies increasingly important. The research aligns directly with the objectives of the ANRF–Maharashtra Water Programme by promoting sustainable drinking water technologies, enhancing water-use efficiency, strengthening climate resilience, encouraging interdisciplinary research, and supporting the development of affordable indigenous technologies with strong commercialization potential. A major novelty of the proposed project is the integration of Rainwater Harvesting (RWH) with Atmospheric Water Generation into a unified smart water management platform. Another important innovation of the proposed project is the development of a modular indigenous technology platform capable of producing 5–500 litres of potable water per day, enabling applications ranging from individual households to schools, healthcare centres, remote villages, disaster relief camps, and community drinking water kiosks. The proposed research is expected to generate high-impact scientific knowledge, indigenous technologies, patents, publications, technology transfer opportunities, startup ventures, and policy recommendations

1. Introduction

Water is one of the most critical natural resources for sustaining human health, agriculture, industrial development, and ecological balance. However, increasing population growth, rapid

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*Corresponding author name and email: Amol Yadav, amolyadav@jspmjscoe.edu.in

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urbanization, climate change, and unsustainable groundwater extraction have significantly intensified water scarcity across many parts of the world. Maharashtra, one of India's largest and most economically important states, is particularly susceptible to recurring water shortages due to its highly variable rainfall patterns, frequent droughts, uneven spatial distribution of water resources, and increasing demand for potable water. Atmospheric moisture represents an abundant and renewable freshwater resource that remains largely untapped. The Earth's atmosphere continuously contains approximately 12,900 km^3 of water vapor, which is naturally replenished through the hydrological cycle and is available irrespective of the presence of rivers, lakes, or groundwater. Atmospheric Water Harvesting (AWH) technology offers a promising decentralized approach for extracting potable water directly from ambient air, particularly in regions facing water stress.

Despite considerable advances in Atmospheric Water Harvesting technologies, existing systems are constrained by several challenges, including high energy consumption, poor performance under fluctuating humidity conditions, intermittent operation, limited integration of renewable energy sources, and insufficient attention to drinking water quality monitoring and treatment. These limitations restrict their widespread adoption for rural and community-scale applications in Maharashtra. Recent advances in high-efficiency refrigeration systems, advanced desiccant materials, solar thermal technologies, microchannel heat exchangers, intelligent sensing, and Artificial Intelligence (AI) provide an opportunity to overcome these limitations. Integrating these technologies into a hybrid atmospheric water generation system can substantially improve water production efficiency, reduce energy consumption, and enable operation under diverse climatic conditions. Furthermore, AI-based predictive control and digital twin technologies can optimize system performance by adapting operation to changing temperature, humidity, solar radiation, and user demand in real time. In the proposed research, the development of an Intelligent Solar Hybrid Atmospheric Water Harvesting System integrating renewable energy, advanced hygroscopic materials, artificial intelligence, thermal energy storage, and real-time water quality monitoring presents a sustainable and innovative solution for providing safe drinking water in drought-prone regions of Maharashtra. Such a system has the potential to reduce dependence on groundwater, improve drinking water security, enhance climate resilience, and contribute toward achieving the objectives of Sustainable Development Goals (SDG 6) Clean Water and Sanitation. Rainwater is the primary natural source of freshwater and plays a fundamental role in sustainable water resource management. Therefore, effective utilization of rainfall during the monsoon season represents the first step towards achieving water conservation and reducing dependence on conventional water sources. In the proposed project, an integrated Rainwater Harvesting (RWH) system will be developed in conjunction with the solar photovoltaic (PV) installation. The solar panels will serve a dual purpose by generating renewable electricity while simultaneously functioning as efficient rainwater collection surfaces. A specially designed gutter and collection network will channel the harvested rainwater through a first-flush diversion unit followed by sediment filters, activated carbon filtration, and other pre-treatment stages to remove suspended solids and contaminants before it enters the advanced purification system. The treated water will subsequently undergo UV disinfection and mineralization to ensure compliance with BIS IS 10500 (2012) drinking water quality standards.

2. Literature Review

Atmospheric Water Harvesting (AWH) has emerged as a promising technology for addressing drinking water scarcity in regions with limited access to conventional freshwater resources. Over the last decade, significant research efforts have been directed toward developing sustainable systems capable of extracting moisture from ambient air using condensation, sorption, radiative cooling, membrane-based processes, and hybrid technologies. The increasing frequency of droughts, climate variability, and the growing demand for decentralized drinking water solutions have accelerated research worldwide, particularly in the United States, China, Saudi Arabia, Singapore, Australia, and several European countries. Recent comprehensive reviews by Saha (2026) et al. and Wang (2025) et al. have highlighted the rapid expansion of this field and emphasized the need for integrated, climate-responsive, and energy-efficient AWH systems.

Among the available technologies, vapor-compression refrigeration-based atmospheric water generators are the most commercially mature due to their ability to produce relatively large quantities of water under moderate to high humidity conditions. Recent studies have focused on improving system efficiency through high-performance heat exchangers, inverter-driven compressors, eco-friendly refrigerants, optimized airflow management, and compact condenser designs. However, the relatively high specific energy consumption of conventional refrigeration-based systems continues to limit their widespread adoption, particularly in rural and off-grid locations. In this context, Çerçi (2025) et al. compared several photovoltaic-supported hybrid configurations and demonstrated that system-level integration can improve performance, although intelligent optimization and adaptive control remain largely unexplored. To overcome these limitations, sorption-based atmospheric water harvesting has gained considerable research attention. Recent investigations have explored advanced desiccant materials such as silica gel, zeolites, activated alumina, metal-organic frameworks (MOFs), hygroscopic salts, and composite sorbents with enhanced adsorption capacity and lower regeneration temperatures. Continuous dual-bed and rotary desiccant systems have demonstrated improved water productivity by enabling simultaneous adsorption and regeneration. Solar-assisted regeneration using flat-plate and evacuated-tube collectors has further reduced electrical energy requirements, making sorption technologies increasingly attractive for sustainable drinking water production. Sadek (2026) et al. demonstrated a continuous dual-chamber sorption-based system using silica gel and finned heat exchangers, showing that simultaneous adsorption and desorption can significantly improve water productivity and thermal efficiency. Mohammed Ali (2024) et al. reviewed carbon-based composite sorbents and identified strong potential for solar-driven AWH.

Hybrid atmospheric water harvesting systems combining desiccant dehumidification with vapor-compression refrigeration have recently emerged as an effective solution for improving performance under varying climatic conditions. These integrated systems utilize desiccants to reduce latent cooling loads before condensation, thereby increasing water yield while reducing compressor power consumption. Several researchers have also investigated photovoltaic-powered systems, hybrid solar thermal-photovoltaic configurations, thermal energy storage, and passive radiative cooling techniques to enhance energy efficiency and enable continuous operation under diverse environmental conditions. Xu (2024) et al. demonstrated an integrated system combining solar heating and radiative cooling for all-day water production, while Nishad (2025) et al. reviewed passive radiative cooling approaches and concluded that such systems require hybridization to achieve practical water productivity. Agrawal (2023) et al. experimentally investigated a solar-assisted evacuated-tube collector for AWH and showed improved thermal regeneration, but continuous operation and intelligent control were not addressed. Recent review articles indicate growing interest in advanced materials for atmospheric water harvesting, including graphene-based composites, carbon nanotubes, mesoporous carbons, hydrogel-based sorbents, and nanostructured condensation surfaces. These materials have demonstrated significant improvements in moisture adsorption, condensation efficiency, corrosion resistance, and long-term durability. Parallel developments in microchannel heat exchangers, surface coatings, anti-fouling materials, and additive manufacturing have further contributed to the development of compact and high-performance atmospheric water harvesting systems. Alenezi (2026) et al. provided a detailed review of thermoelectric cooling-based AWH and emphasized the importance of condenser design and advanced materials, while also identifying the need for experimental validation of emerging concepts. Mohammed Ali (2024) et al. similarly highlighted the promise of carbon-based sorbents but noted that material development has often progressed faster than complete system integration.

Artificial Intelligence (AI), Internet of Things (IoT), and digital technologies are increasingly being explored to improve system operation and predictive maintenance. Machine learning techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forests, and deep learning models have shown potential for predicting atmospheric conditions, estimating water production, optimizing compressor operation, and reducing overall energy consumption. IoT-enabled sensor networks facilitate real-time monitoring of temperature, humidity, airflow, pressure, and system performance, enabling remote diagnostics and intelligent operational control. Nevertheless, most reported AI applications remain at the simulation or proof-of-concept stage, with limited experimental implementation in fully integrated atmospheric water harvesting systems. Alenezi (2026) et al. specifically noted that AI opportunities in thermoelectric AWH are promising but remain largely conceptual, while Agyekum (2024) et al. also identified the lack of experimental validation and intelligent system integration as a major research gap. Another important area of international research is renewable energy integration. Numerous studies have evaluated the use of photovoltaic systems, solar thermal collectors, phase change materials (PCM), and hybrid renewable energy configurations to reduce dependence on grid electricity. These approaches have demonstrated improved sustainability and lower operational costs, particularly for remote and off-grid communities. However, challenges remain in optimizing system performance under fluctuating weather conditions and seasonal climatic variations. Çerçi (2025) et al. showed that photovoltaic-supported hybrid systems can improve overall performance, while Xu (2024) et al. demonstrated the feasibility of combining solar heating with radiative cooling for extended operation. Despite these advances, robust adaptive control strategies and long-term field validation are still lacking.

International studies have incorporated sediment filtration, activated carbon filters, ultraviolet disinfection, mineralization cartridges, and microbial quality assessment to ensure compliance with drinking water standards. Continuous online water quality monitoring integrated with intelligent control systems remains relatively underdeveloped, particularly for decentralized community-scale applications. Wang (2025) et al. emphasized that commercial and research systems often focus on water production metrics while giving limited attention to water quality assurance. Saha (2026) et al. pointed out that future AWH systems must integrate water quality management with renewable energy and intelligent operation to be viable for real-world deployment. Despite substantial technological progress, several critical research gaps remain. Existing systems often optimize only individual components rather than the complete water-energy system. Comprehensive integration of advanced desiccant materials, high-efficiency refrigeration, solar thermal regeneration, photovoltaic power, thermal energy storage, AI-based adaptive control, IoT-enabled monitoring, digital twins, and real-time drinking water quality assessment has received limited attention. Additionally, very few studies have demonstrated long-term field performance across diverse climatic conditions or evaluated socio-economic feasibility for rural and semi-urban communities in developing countries. The recent reviews by Saha (2026) et al., Wang (2025) et al., and Agyekum (2024) et al. collectively underline that the field is advancing rapidly, but the transition from component-level innovation to fully integrated, intelligent, and field-ready systems remain incomplete.

These research gaps provide a strong opportunity for developing an indigenous, climate-resilient, solar-assisted hybrid atmospheric water harvesting platform that combines advanced thermal engineering, renewable energy, intelligent control, and water quality assurance. Such an integrated approach aligns with current international research trends while addressing the practical requirements of sustainable, decentralized drinking water production under varying climatic conditions. The table 1 shows the summary for international researches.

3. Design Methodology

3.1 Importance of the proposed project in the context of current status

The proposed project addresses the critical gaps through the development of an AI-enabled Solar-Assisted Hybrid Atmospheric Water Generation System that integrates advanced desiccant-based dehumidification, high-efficiency heat pump technology, microchannel heat exchangers, evaporative cooling, solar photovoltaic and solar thermal energy, thermal energy storage, IoT-enabled sensing, Digital Twin technology, and intelligent adaptive control. The proposed system will continuously monitor ambient temperature, humidity, solar radiation, water demand, and energy availability to optimize operating parameters, thereby maximizing water production while minimizing energy consumption. Continuous online monitoring of drinking water quality, UV disinfection, mineralization, and predictive maintenance will further enhance system reliability and ensure compliance with BIS drinking water standards.

3.1.1 Overall Methodology and Research Framework

The proposed research aims to develop an Independent AI-Driven Climate-Resilient Smart Cost-Effective Drinking Water System by integrating Atmospheric Water Generation (AWG), Rainwater Harvesting (RWH), Renewable Energy, Artificial Intelligence (AI), Internet of Things (IoT), Digital Twin Technology, and Smart Water Quality Monitoring into a unified and autonomous drinking water platform. Unlike conventional Atmospheric Water Generators, which rely solely on ambient air moisture throughout the year, the proposed system adopts a multi-source water harvesting strategy. During the monsoon season (approximately June to September in Maharashtra), rainwater will be harvested, treated, and stored as the primary source of drinking water. During the remaining dry months, the system will automatically switch to atmospheric water generation. This intelligent seasonal source-switching strategy is expected to significantly reduce electricity consumption, operational costs, and equipment wear while ensuring a reliable year-round supply of potable water. The proposed methodology follows a systems engineering approach comprising seven interconnected research modules: (i) climatic assessment and water demand analysis, (ii) hybrid atmospheric water generation and rainwater harvesting system development, (iii) renewable energy integration, (iv) AI-based decision support and Digital Twin modelling, (v) smart water treatment and quality monitoring, (vi) prototype development and experimental validation, and (vii) multi-location field demonstration and performance evaluation. Each module is designed to operate independently while exchanging real-time information through a centralized intelligent controller. The integrated framework will continuously optimize water production, energy utilization, storage management, and water quality based on climatic conditions and user demand.

The annual drinking water demand will be estimated for different user categories, including individual households, schools, healthcare centres, community drinking water kiosks, and disaster-relief shelters. Water demand estimation will consider population, climatic conditions, seasonal consumption patterns, and storage requirements. Simultaneously, the rainwater harvesting potential will be estimated using rooftop area, rainfall intensity, runoff coefficient, and storage capacity. The annual harvestable rainwater volume will be determined using Equation (1):

$$V = A\,R\,Cr \qquad (1)$$

Where:

V: Harvestable rainwater volume
A: Catchment area (e.g., horizontal roof projection in square meters)
R: Mean annual rainfall depth (in mm for liters, or in meters for m3)
Cr: Runoff coefficient (dimensionless fraction representing collection efficiency)

3.2 Major Design Improvements

The atmospheric water generation potential will be evaluated using psychrometric analysis of ambient air. Moisture availability, dew point temperature, humidity ratio, and latent heat of condensation will be calculated under different climatic conditions to determine the theoretical water production potential. These analyses will establish the operating envelope of the proposed hybrid system and identify the optimal seasonal operating strategy. The main intention is to maximize condensate (water) production over a wide range of ambient conditions while minimizing energy consumption. From an engineering perspective, the problem involves simultaneous optimization of refrigeration, heat transfer, air-side flow, psychrometrics, and condensate management can be solved using Figure 1.

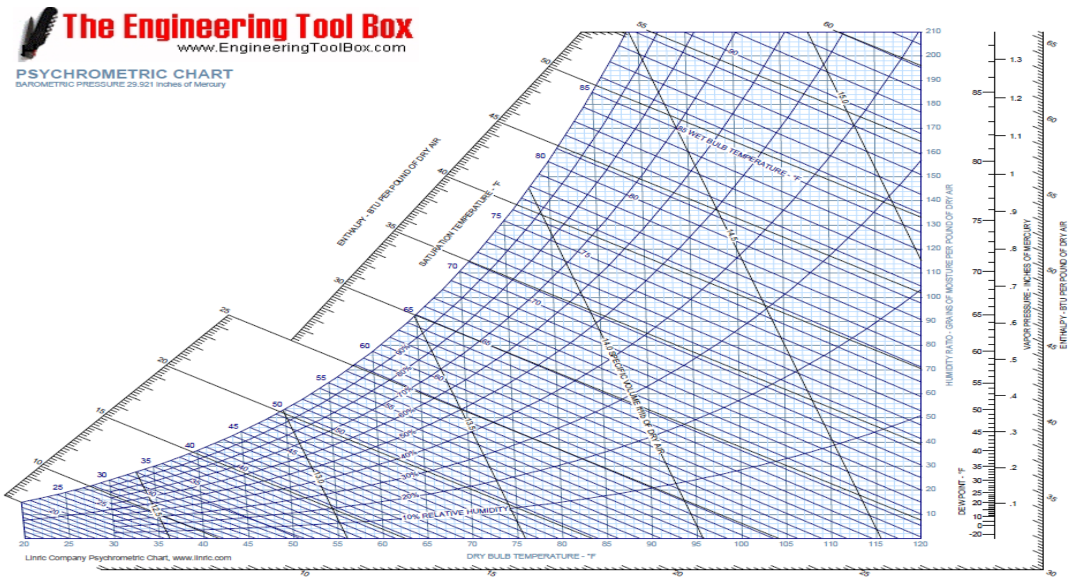

Fig. 1. Psychrometric chart for AWG potential estimation

3.2.1 Maximum Water Generation

The rate of water generation depends upon the location, dry bulb and wet bulb temperature and humidity content in the air. The rate of water production depends primarily on:

$$\dot{m}_w = \dot{m}_{air} (W_{in} - W_{out}) \qquad (2)$$

Where, $\dot{m}_w$= condensate production (kg/s), $\dot{m}_{air}$ = dry air mass flow rate and W = humidity ratio (kg water/kg dry air)

Therefore, water production can be increased by following factors:

- Increasing air flow
- Increasing moisture removal per kilogram of air
- Improving heat exchanger effectiveness
- Reducing refrigerant losses
- Minimizing re-evaporation

3.2.2 Increase Evaporator Surface Area

The evaporator is the most critical component in the vapour compression or any refrigeration system where the cooling effect is produced. The improvements can be made in the existing system with larger finned surface, higher fin density, hydrophilic coating, staggered tube arrangement and multi-row evaporator. The optimized results benefit in terms of more condensate production and good heat transfer. The evaporator temperature will be maintained at 5–8°C below dew point temperature of air in that location.

3.2.3 Variable Speed DC Compressor

The compressor is the heart of the refrigeration system. Instead of ON/OFF control, BLDC inverter compressor will be used. This will result into following advantages.

Advantages

- Maintains optimum evaporator temperature
- Better COP
- Lower power consumption
- Higher daily water yield

3.2.4 Intelligent Fan Speed Control

The heat transfer depends on the air flow velocity. The forced convection provides more heat transfer coefficient that natural convection. CFD can optimize the flow at duct inlet, outlet duct, dead zones and bypass flow. The uniform airflow over entire evaporator is maintained for optimized cooling.

3.2.5 Hydrophilic Coated Evaporator

Normal aluminum fins retain droplets. Therefore, in the design, hydrophilic coating will be provided to merge droplets quickly, faster drainage, less air blockage and higher efficiency. Commercial AWGs commonly use blue hydrophilic fins. The poor drainage reduces performance of AWG. The design features will include inclined fins, smooth drain channels, no water retention and antimicrobial coating.

3.2.6 Electronic Expansion Valve (EEV)

The function of expansion valve is to reduce the pressure from condenser to evaporator. As compared to capillary tube, Electronic Expansion Valve (EEV) is suitable which benefits for adjusting refrigerant flow rate as per the load on the evaporator, maintains superheat after evaporator exit to avoid the wet compression in the compressor, adapts to changing weather and for higher efficiency during seasonal variations.

3.2.7 Refrigerant Selection

The refrigerant selection is the critical task in any refrigeration project. The refrigerant will be selected on the basis of environmental, operating and energy efficiency point of view. The desired refrigerant properties considered will be high latent heat, low GWP and good COP and zero ozone depletion potential. The possible refrigerants used may be R1234yf, R1234ze(E), R290 (excellent efficiency but flammable) and R32

3.2.8 Pre-cooling Incoming Air

Incoming air may be pre-cooled using exhaust cold air, heat pipe and regenerative heat exchanger. This reduces refrigeration load and COP will increase.

3.2.9 Heat Pipe Assisted Cooling

A passive heat pipe can be used for precool of incoming air and reheat of outgoing air which will results into lower compressor work, improved COP and higher condensate production.

3.2.10 Microchannel Heat Exchanger

Compared with round copper tube-fin, microchannel condensers are efficient due to higher heat transfer coefficient and lower pressure drop per unit length of pipe. Different passes can be provided along the condenser for reducing pressure drop. The headers can also be provided to minimise the fluctuation in refrigerant. The advantages of microchannel condenser and evaporator are higher heat transfer coefficient, reduced refrigerant charge, lighter and more compact for same tonnage capacity.

3.2.11 CFD-Based Optimization

CFD is a technology where we can predict the flow of refrigerant and air in all the components in the system. The CFD will provide the post processing in terms of different parameters such as stream lines, velocity potential lines, determination of heat transfer coefficient, heat flux etc. The nnumerical optimization of fin spacing, tube spacing, air velocity, pressure drop, condensate drainage and temperature distribution. The software used will be ANSYS Fluent/Simulia/STAR-CCM+/ COMSOL.

3.2.12 Maximum Moisture Capture Control

Different sensors will be used for predicting and analysing of temperature, humidity, refrigerant pressure, evaporator temperature and compressor current. The will control the dew point of air, optimum evaporator temperature, compressor speed and fan speed.

3.3 System Design Philosophy

The proposed technology will be designed as a modular Smart Water Hub capable of producing 5, 20, 50, 200, and 500 litres of potable water per day, enabling deployment across multiple application scenarios. The system architecture incorporates three major subsystems: (i) water generation and harvesting, (ii) renewable energy and intelligent control, and (iii) water purification and storage. The AI controller will continuously evaluate rainfall availability, atmospheric humidity, stored water volume, weather forecasts, solar energy generation, battery status, and water demand to determine the most energy-efficient operating mode. Unlike existing systems that operate continuously irrespective of environmental conditions, the proposed Smart Water Hub will automatically prioritize rainwater utilization during the monsoon season and activate atmospheric water generation only when stored rainwater is insufficient. This climate-responsive operational strategy is expected to reduce the annual operating cost, improve system reliability, and enhance overall sustainability. The modular architecture also allows future integration with groundwater, treated greywater, or municipal water supply if required, making the platform highly adaptable for diverse climatic and socio-economic conditions. The methodology described above establishes the foundation for the subsequent development of the hybrid atmospheric water generation and rainwater harvesting system, renewable energy integration, AI-based optimization, and field validation presented in the following sections.

3.2 Proposed integrated system

The proposed Independent AI-Driven Climate-Resilient Smart Drinking Water System integrates multiple water sources and renewable energy technologies to provide a reliable year-round supply of potable water. The system consists of five major subsystems: renewable energy, atmospheric water generation, rainwater harvesting, intelligent control, and smart water treatment. The renewable energy subsystem combines solar photovoltaic panels, solar thermal collectors, battery storage, and phase change material (PCM) thermal storage. Solar PV supplies electrical power to the compressor, pumps, control units, and sensors, while solar thermal energy provides heat for regeneration of the hygroscopic sorbent. The PCM stores excess thermal energy and enables continuous operation during cloudy periods or at night.The Atmospheric Water Generation (AWG) subsystem employs a hybrid desiccant-assisted heat pump cycle. Ambient air is passed through the adsorption chamber containing hygroscopic composite sorbents that absorb moisture from the air. The saturated sorbent is subsequently regenerated in the desorption chamber using solar thermal energy and auxiliary electric heating when necessary. The released water vapour is condensed using a high-efficiency vapor compression refrigeration system equipped with inverter-driven compressors and microchannel heat exchangers to maximize water recovery and minimize energy consumption. To improve annual efficiency and reduce operating costs, the proposed system incorporates a Rainwater Harvesting (RWH) subsystem. During the monsoon season, rainwater is collected from rooftops through gutters and conveyed to a first-flush diverter to remove initial contaminants. The harvested water is filtered, disinfected, and stored in a smart storage tank. The AI controller continuously monitors rainfall, storage level, and water demand and prioritizes the use of stored rainwater before activating the atmospheric water generation unit. This seasonal water source switching significantly reduces electricity consumption and extends equipment life.

The AI-enabled intelligent control system forms the central decision-making unit of the proposed platform. Using real-time inputs from meteorological sensors, water quality sensors, energy meters, and storage tanks, AI algorithms determine the optimal operating mode. The controller predicts atmospheric water availability, estimates rainwater storage duration, manages renewable energy utilization, schedules compressor operation, and minimizes the specific energy consumption while maintaining uninterrupted drinking water production. The generated water undergoes multi-stage purification, including sediment filtration, activated carbon filtration, optional ultrafiltration, UV disinfection, and mineralization before entering the smart storage tank. IoT-enabled sensors continuously monitor pH, TDS, conductivity, turbidity, temperature, flow rate, and storage level to ensure compliance with BIS IS 10500 drinking water standards. All operating parameters are transmitted to a cloud-based dashboard, enabling remote monitoring, predictive maintenance, and Digital Twin-based performance optimization. The proposed hybrid system is modular and scalable, with capacities ranging from 5 L/day to 500 L/day, making it suitable for households, schools, healthcare centres, community water kiosks, and remote villages.

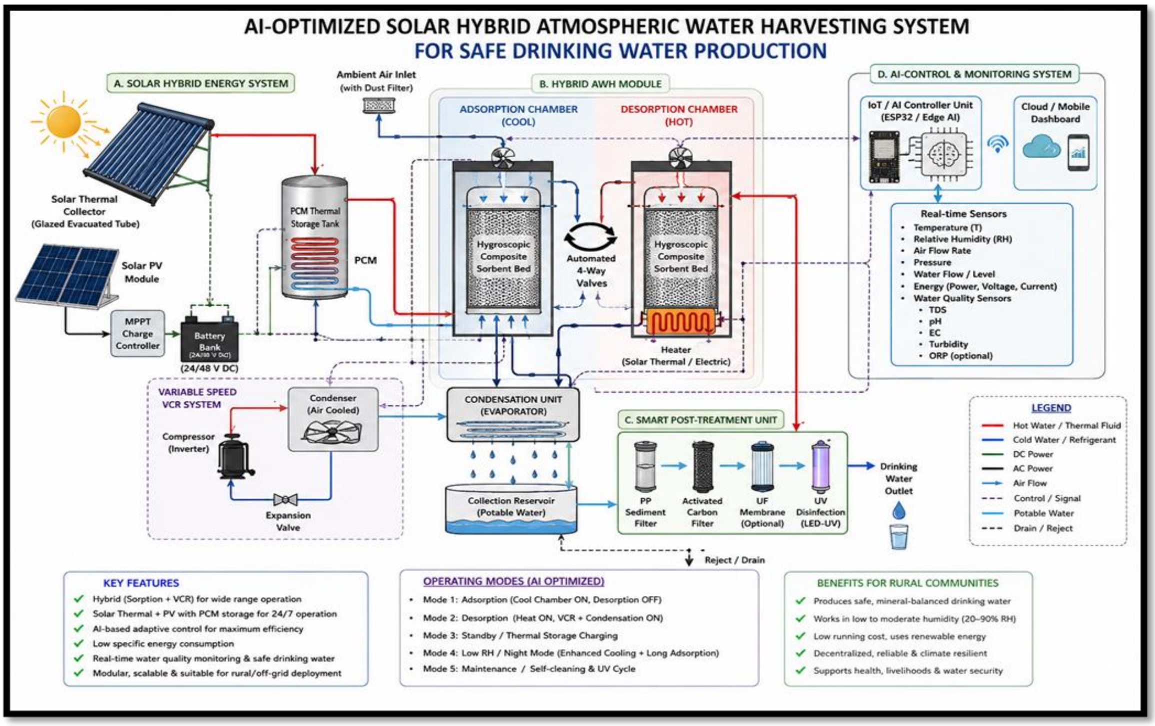

Fig. 2. AI optimized solar hybrid atmospheric water harvesting system

The integration of atmospheric water generation, rainwater harvesting, renewable energy, AI, IoT, and Digital Twin technology represents a significant advancement over existing drinking water systems and provides a sustainable, climate-resilient solution for water-stressed regions of Maharashtra. Figure 2 shows the schematic diagram of proposed methodology in the integrated system

4. Conclusions

Suggested Plan of action for utilization of research outcome expected from the project.

Expected Outcomes:

The proposed project is expected to deliver a novel Independent AI-Driven Climate-Resilient Smart Drinking Water System integrating Atmospheric Water Generation (AWG), Rainwater Harvesting (RWH), Renewable Energy, Artificial Intelligence (AI), Internet of Things (IoT), Digital Twin technology, and advanced water purification for decentralized and sustainable drinking water production. The major expected outcomes of the project are:

1. **Development of an indigenous Smart Hybrid Drinking Water System** integrating Atmospheric Water Generation (AWG), Rainwater Harvesting (RWH), solar photovoltaic (PV), solar thermal energy, hygroscopic sorbent materials, heat pump-assisted vapor compression refrigeration, PCM-based thermal energy storage, and intelligent water storage for year-round potable water production.
2. **Development of modular prototype systems** with capacities ranging from 5–500 L/day, suitable for households, schools, healthcare centres, community drinking water kiosks, remote villages, and disaster relief applications.
3. **Development of an AI-enabled Decision Support System (DSS) and Digital Twin platform** capable of real-time optimization of water production, intelligent seasonal switching between rainwater harvesting and atmospheric water generation, renewable energy management, predictive maintenance, and operational decision-making under varying climatic conditions of Maharashtra.
4. **Development of an IoT-enabled Smart Monitoring System** for continuous monitoring of meteorological conditions, system performance, energy consumption, water production, storage level, and drinking water quality using cloud-based data acquisition and remote monitoring.
5. **Development of an advanced multi-stage water purification and disinfection unit** incorporating sediment filtration, activated carbon filtration, ultrafiltration (optional), UV disinfection, and mineralization with continuous online monitoring of pH, TDS, turbidity, conductivity, temperature, and other water quality parameters to ensure compliance with BIS IS 10500 drinking water standards.
6. **Development of intelligent seasonal water management strategies** that maximize rainwater utilization during the monsoon season and automatically switch to atmospheric water generation during dry periods, thereby reducing annual energy consumption, lowering water production cost, extending equipment life, and improving overall system

sustainability.

7. **Experimental performance evaluation and optimization** of the developed hybrid system under different climatic regions of Maharashtra with respect to water yield, specific energy consumption, coefficient of performance (COP), renewable energy utilization, water quality, reliability, and system durability.
8. **Pilot-scale demonstration and field validation** of the developed technology at representative locations in Maharashtra to establish its technical feasibility, climate resilience, and suitability for decentralized drinking water supply in rural and drought-prone areas.
9. **Comprehensive techno-economic, environmental, and life-cycle assessment** to evaluate capital cost, operating cost, cost of water production, carbon footprint reduction, payback period, environmental benefits, and commercialization potential of the proposed technology.
10. **Generation of high-impact research outputs**, including SCI/SCIE-indexed journal publications, conference presentations, patents, design registrations, software/IP related to AI algorithms, trained manpower (Ph.D., M.Tech., and UG students), technology transfer opportunities, startup incubation, and industry partnerships.
11. **Creation of an indigenous, scalable, climate-resilient drinking water technology platform** that supports water security, reduces dependence on groundwater and tanker water, promotes renewable energy utilization, and contributes to sustainable water resource management, climate adaptation, and rural development in Maharashtra and other water-stressed regions of India.

Suggested plan of action for utilization of research outcomes

The developed technology will be translated into a commercially viable Smart Water Hub through pilot demonstrations, industry collaboration, and technology transfer. The validated prototypes will be deployed at selected schools, healthcare centres, villages, and community drinking water kiosks across Maharashtra to demonstrate year-round operation under diverse climatic conditions. The project team will pursue patent protection, licensing agreements, and startup incubation for commercialization of the developed system. Partnerships with government agencies, rural water supply departments, industries, and non-governmental organizations will facilitate large-scale deployment of the technology in drought-prone and water-scarce regions. The AI software, Digital Twin platform, and IoT monitoring system developed under the project will support remote operation, predictive maintenance, and data-driven water management. The project outcomes are expected to contribute to national missions on Jal Jeevan Mission, Net Zero and Sustainable Development Goals (SDGs 6, 7, 9, 11, and 13) while creating opportunities for indigenous manufacturing, skilled manpower development, entrepreneurship, and sustainable drinking water security.

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