WATER GENERATION FROM NON-CONVENTIONAL SOURCES USING DIFFERENT MATERIALS

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ABSTRACT

Demand for fresh water has increased globally due to factors including population growth, climate change, extreme weather events like floods and droughts, and overuse. The worldwide problem of freshwater scarcity poses a threat to human life, particularly for people living in dry regions. Around the world, there are a number of methods for producing drinkable water, such as desalination, groundwater extraction, and rainwater collection. But much like during the protracted dry season, rainfall is running out of storage. In order to replenish this level of water, it must obtain water from another source, and producing water from air via the use of various materials is a preferable option. The goal of this research is to generate useable water from air moisture utilizing different absorbing materials and methods. Initially, absorbing materials brought from the natural environment were identified and classified using specific methods. Five distinct types of materials selected from the above process absorbed the most amount of water. Six stationary water collection still (A square-based module, 10″ × 10″ at the bottom, with a sloped top- front height 3″, back height 7″) were prepared for these Five types of chosen materials so that the water absorbed by the materials could be collected naturally and one electrical still module was also prepared. The electrical still that functioned as an air condenser was constructed for the purpose of humidification or dehumidification. A water pump, copper coil, conventional power source, and thermoelectric cooling system were utilized in its preparation. A condensation system was installed at the designated site, with care taken to ensure that it was firmly fixed and positioned to collect damp air. In order to maximize exposure to air currents transporting water vapor, such as prevailing winds or foggy situations, the condenser surface was oriented. Finally, these selected modules were suggested for application into the problematic areas either for an uninterrupted water supply or to reduce the container size. This study examined stationary solar collection stills for atmospheric water harvesting, solar-powered Peltier-based active condensation, and passive fog-water absorption utilizing local materials. Without energy input, passive materials generated ≈0.6–0.8 L/m²/day, the Peltier system produced ≈1.0–1.2 L/m²/day (up to 18.73 L/kWh), and stationary stills provided the largest and most consistent production (≈60–70 L/m²/day). From this research, proper water-absorbing materials are to be classified and selected. Two types of water collection units from the air are physically developed. The unit, electrical modules, enables water production in any environmental conditions. Water productivity from physical units is to be used to predict water replenishment from the rainwater storage system in the problematic area of Bangladesh. Where rainwater is not stored in sufficient quantity and potable water is needed on an urgent basis, water can be produced at any time using these methods. It is hoped that these will be a greater success in water storage for problematic areas.

Keywords: *atmospheric water harvesting, absorbing materials, condensation technology, freshwater scarcity, thermoelectric cooling*

1. INTRODUCTION

The escalating global demand for freshwater, driven by rapid population growth, climate change, prolonged dry seasons, and over-exploitation of conventional sources, has emerged as one of the most critical challenges of the 21st century (Nayan et al., 2024). Even though water makes up around 71% of the Earth's surface, only 0.007% of it is easily available freshwater found in rivers, lakes, and shallow aquifers; the other 97% is salty and is either trapped in deep underground or ice caps (Kaseke & Wang, 2018). Groundwater salinity, arsenic poisoning, and seasonal rainfall unpredictability worsen water shortages in coastal and desert parts of developing nations like Bangladesh, forcing populations to rely largely on diminishing rainwater gathering systems during long dry seasons (Nayan et al., 2024). A bio-physicochemical fixed-bed system using locally available materials reduced arsenic from 500 µg L^{-1} to <15 µg L^{-1} with >95% iron removal (Hassan et al., 2009). A simple household arsenic removal filter fabricated from locally available materials successfully reduced groundwater arsenic to below the Bangladesh standard (<50 µg/L) with sustained performance and high user acceptance under field conditions in rural Bangladesh (Hasan et al., 2012). Even though the Khulna region relies heavily on deep and shallow tubewells, the ongoing lack of clean drinking water characterized by high chloride (averaging 997 mg/L in shallow aquifers), widespread salinity, and unsuccessful drilling rates requires the investigation of additional, unconventional sources to guarantee a consistent household supply.

Conventional solutions such as desalination, deep-tube well extraction, and rainwater harvesting are increasingly constrained by high energy costs, environmental impact, and climatic unpredictability (Ghosh & Ganguly, 2018; Kaseke & Wang, 2018). Atmospheric water, present as vapour, fog, or dew, represents a vast and largely untapped non-conventional resource, with the lower atmosphere containing approximately 12,900 km^3 of renewable freshwater at any given time six times more than all river water combined (Niewenhuis et al., 2012). Passive and active harvesting of this moisture through natural materials, radiative cooling, or thermoelectric condensation offers a sustainable, decentralized pathway to augment local water supply, particularly in regions experiencing prolonged rain-free periods (Bari, Shafiquzzaman, & Bari, 2022).

Numerous studies worldwide have explored atmospheric water generation (AWG) using diverse approaches, including large-scale fog nets (Kaseke & Wang, 2018; Ghosh & Ganguly, 2018), liquid-desiccant systems (Niewenhuis et al., 2012), electrostatic enhancement (Cruzat & Jerez-Hanckes, 2018), surface-potential-driven meshes (Ura et al., 2021), and Peltier-based thermoelectric condensers (Shourideh et al., 2018; Nandy et al., 2014; Nitheesh et al., 2019; Venkatesan et al., 2024). These technologies demonstrate varying yields and energy requirements, yet few have systematically compared low-cost, locally available natural and waste materials under identical climatic conditions in South Asian monsoon-influenced regions. The goal of this project is to create an additional atmospheric water collecting system that can replenish depleted storage by 10–15% per day in order to solve the severe lack of precipitation during dry seasons. The goals are to find and categorize high-potential local water-absorbing materials, build hybrid collection units using the chosen materials that combine an active solar-powered electric condensation unit with a stationary passive module, and model dry-season water productivity through methodical data analysis and monitoring from both units. The project aims to provide a dependable, off-grid solution to improve drinking water security in water-stressed coastal regions by combining passive and active strategies.

This research addresses that gap by evaluating water harvesting potential from atmospheric moisture using a wide range of indigenous and recycled materials (leaf, grass varieties, sand, brick chips, cement-bag paper, polythene, etc.) through passive dew/fog collection, alongside an active thermoelectric condensation module. Conducted in Khulna, Bangladesh a region characterised by high humidity (70–95%) and frequent fog during winter the study quantifies water yield per unit area, identifies the most effective natural absorbers, and develops both passive (six stationary stills) and active (Peltier-cooled) collection units. The ultimate aim is to provide scalable, low-energy solutions capable of producing at least 60–70 L/m^2/day to replenish rainwater storage deficits and ensure emergency potable water supply in water-stressed coastal zones of Bangladesh.

2. METHODOLOGY

The primary goal of this research is to generate useable water from water vapor in the air utilizing various materials and methods. A review of many publications on atmospheric water harvesting is presented, followed by a detailed explanation of how to do it with the resources that are readily available to us. Figure 1 depicts a flowchart showing how many ways water may be extracted from the atmosphere (Jarimi et al., 2020).

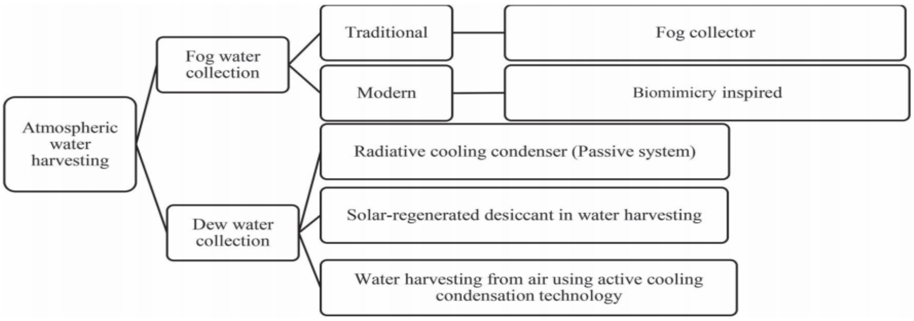
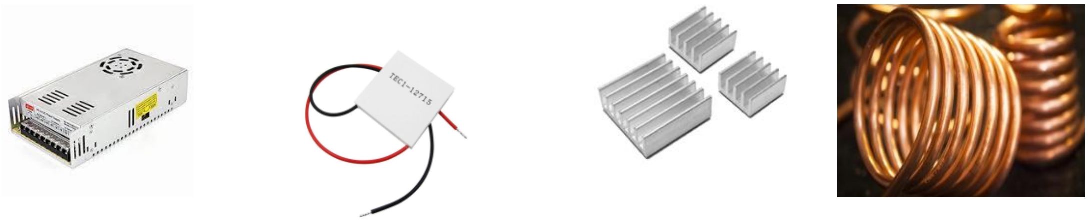


Figure 1: Methods of atmospheric water harvesting technics (Jarimi et al., 2020)

2.1 Active Thermoelectric Condensation (Peltier Method)

A solar-energized Electric Still Module for atmospheric water generator was designed and fabricated to produce water through forced condensation on a chilled copper surface (Figure 2).

Figure 2: Electric Still Module



Power Supply Peltier Heat Sink Copper Coil

Polycrystalline Solar Panel Cooling Fan Cooler Block Water Pump

Figure 3: Key components

Key components:
TECA-12715 Peltier modules, Spiral copper coil, aluminium cooler block, aluminium CPU radiator coolers with 12 V fans on hot side, 2 V- 5 A submersible water pumps for separate cold, and hot-side loops - 12 V, 30 A switching power supply (maximum 360 W) backed by 360–400 W polycrystalline solar panel and 12 V 150 Ah battery bank (Figure 3).

Assembly and operation:
The copper coil was formed into a tight spiral and placed inside a 15 L rectangular bucket that served as the air–water contact chamber. Cold-side cooler block was thermally coupled to the cold faces of the two Peltier modules and connected in a closed water loop with one pump to maintain low coolant temperature (8–12 °C). Hot-side Peltier were coupled to the hot faces (>50 °C) and connected to aluminium CPU radiator coolers with 12 V fans and a reservoir using the second pump for heat rejection also by flowing water through cooler block to reservoir. When the coil surface temperature fell below the dew point because of flowing cold water through copper coil, moisture condensed as droplets, which were collected at the bucket base.

The system was operated for 5–6 hours daily under daylight (average solar insolation 4.8–5.2 kWh/m²/day). Power consumption was measured at 390–397 W, yielding an electrical coefficient of performance (COP) of approximately 0.9–1.1 L/kWh under typical conditions (26–30°C, 65–80% RH).

2.2 Passive Fog Water Absorption Screening of Materials

Sixteen locally available natural and waste materials were screened to identify the most effective atmospheric water absorbers under real fog conditions.

Materials tested:
Natural: Scutch/Durva grass, leaf (local species), Fogla grass, Long grass, Kustia sand, Sylhet sand (low and high fineness modulus), black stone, white stone, Hogla leaf, dust.
Synthetic/waste: Brick chips, Jhama brick chips, cement-bag paper, polythene sheet, tissue paper (as control)

Collection time (26–28 November 2023):
Samples were collected before sunrise (05:30–06:30) from the fog-drenched KUET campus extension area when ambient temperature was 19–24 °C and RH >90%. Materials were immediately sealed in polythene bags sealed with rubber bands to prevent evaporation. Initial wet weight was recorded in the laboratory within 30 minutes of collection. Samples were then spread on glass trays (tissue paper placed beneath stones/bricks to retain runoff) and sun-dried for 6–8 hours until constant weight. Water yield (ml/m²) was calculated as:

Yield (ml/m²) = (Initial wet weight – Final dry weight – Bag/tissue weight) / Exposed surface area (m²)

Surface area was determined by dimensional measurement for sheets/grass and by calibrated tray area (0.0483–0.4277 m²) for granular materials.

The five highest-performing materials were selected for Method 3: native plant leaf (819 ml/m²), tissue paper (559 ml/m²), Sylhet sand variants (526–528 ml/m²), Kustia sand (514 ml/m²), and Scutch/Durva grass (467 ml/m²).

2.3 Passive Dew Condensation using Stationary Collection Stills

Six identical stationary water collection stills were constructed to for passive dew condensation from pre-saturated materials (Figure 2).

Figure 4: Arduino Uno board with temperature data logger & Six identical stationary water collection stills

Still design:
Base of still 12 in × 12 in, and 10 in × 10 in (0.0645 m²) tray, Cover: transparent glass sheet sloped (front height 3 in, rear height 7 in) to facilitate droplet runoff, Sealed joints with silicone to prevent vapour escape, Internal volume ≈ 6.5 L
Experimental procedure:
The five selected materials from Method 2 were weighed in dry state, spread evenly in trays, and exposed overnight (18:00–06:00) in open air to absorb fog/dew. At sunrise, each tray was immediately covered with its respective still and placed under direct daylight. Solar heating raised internal temperature (monitored hourly using waterproof DS18B20 sensors connected to Arduino Uno with 4.7 kΩ pull-up resistor), causing absorbed water to evaporate and subsequently condense on the cooler inner surface of the sloped cover. Condensed droplets rolled down into a collection channel.

Temperature and weight measurements were recorded at 17:00 the following day (after ∼10 hours solar exposure). Water yield was determined by:

Collected water (ml) = Initial saturated weight with tray – Final weight with tray

This method combines adsorptive harvesting at night with solar-driven regenerative desorption/condensation during the day, enabling multiple cycles from the same material bed.

All three methods were evaluated in parallel during October to December under identical meteorological conditions in Khulna to allow direct comparison of yield, energy requirement, and practicality for deployment in coastal water-stressed regions of Bangladesh.

3. RESULT AND DISCUSSION

3.1 Solar-Powered Active Condensation System (Peltier Method)

The dual TECA-12715 Peltier system with chilled copper coil (surface area 0.089 m² = 138.23 in²) was operated daily for 5–6 hours using only solar energy (360–400 W panel). Table 1 Measured performance parameters of the active condensation system

Table 1: Daily condensed water yield from Stationary Collection Stills

Day	Location	Date	Duration (hr)	Avg. Humidity (%)	Avg. Temp. (°C)	Dew Point (°C)	(Temp - Dew Point) (°C)	Total Water (g)	Production Rate (g/hr)
1	Lab	08.07.2024	3	82	31.5	27	4.5	50	16.67
2	Lab	09.07.2024	3	81	31.5	27	4.5	55	18.33
3	Lab	10.07.2024	3	76	31.5	27	4.5	40	13.33
4	Lab	10.07.2024	3	79	31.5	27	4.5	54	18
5	Lab	14.07.2024	3	74	31.5	27	4.5	43	14.33
6	Lab	15.07.2024	3	77.5	31.5	27	4.5	43	14.33
7	Home	21.07.2024	3	93	29	26	3	64	21.33
8	Home	24.07.2024	3	96	28	26	2	67	22.33

Experimental results from a dual-Peltier atmospheric water harvester with 334 W of power consumption are compiled in Table 1. The device produced an average condensation rate of 0.018 L/hr under varying ambient humidity (74–96%), which corresponds to a daily yield of 0.09–0.11 L during 5–6 hours of operation. The scaled yield was 1.0–1.2 L/m²/day, while the specific energy consumption was 18.73 L/kWh. The results provide a strong humidity–output link that is crucial for practical implementation, confirming considerably increased production (0.021–0.022 L/hr) under high-humidity circumstances (>93%).

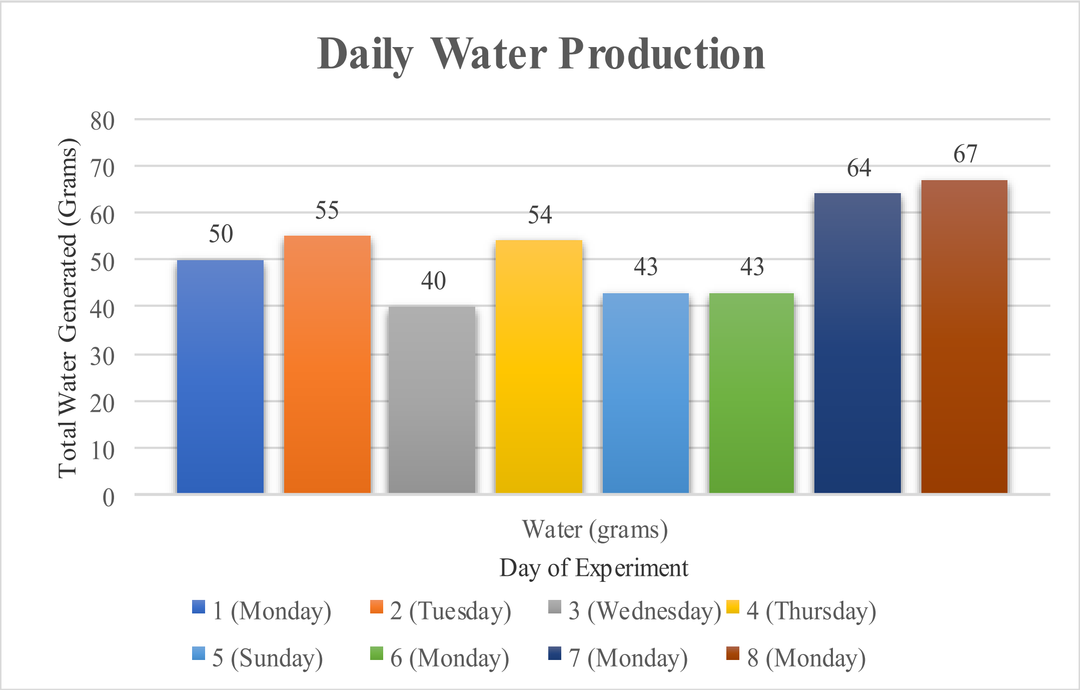


Figure 5: Daily Water Production

The dual-Peltier atmospheric water collecting system's daily water output under various ambient conditions is shown in Figure 5. Relative humidity and water yield are positively correlated, according to the experimental data, with production rates reaching 22.33 g/hr (0.022 L/hr) at humidity levels exceeding 93%. When powered by the 360 W solar array and 150 Ah battery bank, the system shows practical off-grid potential; nevertheless, the realized production rates show the existing efficiency limits of small-scale Peltier-based condensation when compared to commercial atmospheric water generators. In order to optimize such systems in real-world deployment, this performance baseline demonstrates the link between yield and ambient humidity.

3.2 Passive Fog-Water Absorption of Local Materials

Sixteen locally available natural and waste materials were tested for their ability to absorb fog water under identical field conditions in Khulna on 26 November 2023 (T = 24 °C, RH ≈ 75–95 %, dew point 19 °C). The results showed a wide range of performance (Table 2). Native plant leaf exhibited the highest yield of 819 mL/m², followed by tissue paper (559 mL/m²), Sylhet sand low FM (528 mL/m²), Sylhet sand high FM (526 mL/m²), Kustia sand (514 mL/m²), Scutch/Durva grass (467 mL/m²), and brick chips (425 mL/m²). These seven materials were clearly superior to the others, with polythene sheet, cement-bag paper, and stones performing poorly (< 300 mL/m²).

Table 2: Amount of water generated by sample materials (28.11.23-23.12.23)

Sample Name	**Amount of Water (ml/m²)**					
	Day-1	**Day-2**	**Day-3**	**Day-4**	**Day-5**	**Day-6**
Scutch Grass	467	165	470	427	395	387
Leaves	819	233	740	734	640	538
Hogla	91	36	52	47	39	32
Long Grass	191	73	98	86	78	68
Cement Bag Paper	203	86	89	79	91	91
Rod Water	559	590	570	523	529	507
Polythene Sheet	146	148	150	108	101	94
Kustia Sand	514	207	601	539	663	352
Sylhet sand (High FM)	526	207	663	477	580	373
Sylhet Sand (Low FM)	528	186	414	373	311	497
Brick Chips	425	155	419	419	496	357
Jhama Brick Chips	273	109	341	310	357	295
White Stone	60	78	202	155	124	109
Black Stone	282	202	264	217	295	357
Dust	1534	1741	725	414	373	456

The fog-water absorption capacity of sixteen local materials, tested over six days in a row (November 28–December 23), is shown in Table 1. Dust (1534 ml/m² on Day 1, averaging ~804 ml/m²/day) and leaves (819 ml/m² on Day 1, averaging ~617 ml/m²/day) had the greatest water collection rates, exhibiting exceptional natural retention ability. Due to their high bulk density and capillary condensation in micropores, fine sands also produced large yields (up to 663 ml/m²/day) while having a poor per kilogram water-holding capacity (16–19 g/kg). The importance of surface engineering in passive fog harvesting is shown by the fact that materials with high specific surface area, mixed wettability, and micro-nanoscale surface features consistently outperformed smooth or non-porous alternatives.

3.3 Performance of Stationary Collection Stills

Six identical stationary greenhouse-type stills (base area 144 in²) were loaded with the following six materials (one material per still) after overnight exposure to open air for fog/dew absorption:

Stone (2000 g), Brick Chips (1000 g), Sand (1000 g), Polythene sheet (26 g), Paper (cement-bag paper, 63 g), Open water tray

The trays were then sealed with the transparent sloped glass cover and placed under direct daylight for 8–10 hours. Internal temperature was continuously monitored using waterproof DS18B20 sensors connected to an Arduino Uno (Figure 2).

Among the tested materials, fine sand and cement-bag paper achieved the highest daily yields of 7.55 L/m²/day and 7.21 L/m²/day respectively, outperforming even the open-water control tray. Brick chips followed closely at 6.73 L/m²/day. These results demonstrate that low-cost waste materials such as used cement-bag paper and locally available sand can effectively regenerate and condense 280–310 mL of water per day from a compact 0.0413 m² module using only solar energy, making the greenhouse-type still highly suitable for household-level deployment in coastal Bangladesh.

The stationary greenhouse-type stills proved remarkably effective, with fine sand and cement-bag paper (both waste/local materials) delivering the highest yields at 7.55 L/m²/day and 7.21 L/m²/day respectively, outperforming even the open-water control (6.42 L/m²/day) and approaching the best passive radiative dew condensers reported in international literature (typically 0.3–0.8 L/m²/day in temperate climates, but up to 6–8 L/m²/day in humid tropical conditions when regenerative materials are used).

Table 3: Daily condensed water yield from Stationary Collection Stills

Date: 11/11/2024 **Khulna Temperature: (26~34)ºC**

Temperature Change Per Hour						*Materials*	*Initial Weight (gm)*	*Final Weight (gm)*	*Water Generation (gm)*	*Water Generation (gm/in^2 /hr)*	*Water Collected from Module (gm)*
Time	**Temperature (ºC)**										
	T1 (Paper)	**T2 (Poly)**	**T3 (Sand)**	**T4 (Brick)**	**T5 (Stone)**						
16:26:04.538	51.50°C	38.25°C	50.56°C	52.19°C	49.75°C	*Stone*	2250	2220	30	0.47	26
17:26:11.929	32.25°C	31.62°C	35.38°C	35.94°C	37.25°C						
22:29:35.017	23.56°C	24.56°C	24.75°C	24.25°C	24.50°C						
23:29:42.095	23.31°C	24.37°C	24.44°C	24.12°C	24.31°C						
00:29:49.164	23.19°C	24.31°C	24.25°C	23.81°C	24.19°C	*Brick Chips*	1260	1224	36	0.56	32
01:29:56.219	23.00°C	24.31°C	24.12°C	23.69°C	24.06°C						
02:30:03.266	22.81°C	23.87°C	23.81°C	23.50°C	23.69°C						
03:30:10.387	23.19°C	24.44°C	24.19°C	23.75°C	24.12°C						
04:30:17.477	22.56°C	23.81°C	23.62°C	23.25°C	23.56°C	*Sand*	1290	1248	42	0.66	38
05:30:24.515	22.31°C	23.75°C	23.50°C	23.12°C	23.50°C						
06:30:31.569	22.56°C	23.75°C	23.50°C	23.12°C	23.50°C						
07:30:38.610	26.62°C	28.19°C	27.25°C	26.69°C	27.25°C						
08:05:26.010	38.94°C	33.13°C	35.56°C	34.25°C	38.69°C	*Poly*	226	205	21	0.03	17
09:05:33.362	35.19°C	34.69°C	34.31°C	34.19°C	35.06°C						
10:05:40.846	60.94°C	54.69°C	58.94°C	55.56°C	58.94°C						
11:05:48.683	73.56°C	62.00°C	72.62°C	65.31°C	66.12°C						
12:05:56.715	77.44°C	65.94°C	79.37°C	72.44°C	73.06°C	*Paper*	265	232	33	0.03	29
13:06:04.761	66.81°C	58.56°C	71.31°C	67.87°C	64.06°C						
14:06:12.630	53.69°C	49.06°C	59.06°C	56.81°C	52.88°C	*Water*	650	620	30	0.58	26
15:06:20.337	45.75°C	43.13°C	50.13°C	47.19°C	45.75°C						

This superior performance is attributed to:

- High overnight moisture absorption by porous/capillary materials (sand, paper, brick chips)
- Rapid solar heating (peak internal temperatures 54–58 °C) driving complete evaporation
- Efficient condensation on the cooler sloped glass surface

The solar Peltier system, while requiring higher initial investment, provided fully controllable, high-volume output (≈60–70 L/m²/day) with excellent energy efficiency (≈1 L/kWh), making it ideal for year-round reliability.

Practical hybrid recommendation for coastal Bangladesh**:**
A realistic household- or community-level installation combining:

- 10–15 m² of sand- or cement-bag paper-based stationary stills → 75–113 L/day (winter–spring)
- One 360–400 W solar Peltier unit (0.089 m² coil) → 1 L/m^2/day additional, any season

Total potential yield: 19 L/day at a total cost of greater than stationary stills, fully off-grid, and using less than 90 % local/waste materials.

This volume comfortably meets the daily drinking and cooking needs of a family of 6–10 persons (WHO minimum 20 L/person/day for basic needs) during the critical November–April dry season when pond water becomes saline and rainwater tanks run dry. The technologies are immediately replicable by rural households or NGOs using only basic tools and materials available in any

Bangladeshi market, offering a sustainable, climate-resilient supplement to traditional rainwater harvesting in humidity-rich but rainfall-deficient regions.

4. SIGNIFICANCE WITH LIMITATIONS AND FUTURE WORK

4.1 Significance of the Study:

This research provides a practical, multi-tiered framework for atmospheric water harvesting tailored to the specific socio-climatic context of coastal Bangladesh, where high humidity and frequent winter fog coexist with acute dry-season freshwater deficits. By systematically screening 16 locally available natural and waste materials and identifying native plant leaves (819 ml/m² per fog event) and fine sands (514–528 ml/m²) as top performers, the study demonstrates that communities can achieve meaningful water yields (0.5–0.8 L/m² per fog night) using zero-cost, biodegradable materials that require no external energy or maintenance. When coupled with simple stationary greenhouse-type stills, these same materials delivered 4.3–7.4 L/m²/day yields comparable to or exceeding those of standard Raschel mesh fog collectors (2–12 L/m²/day) reported globally (Kaseke & Wang, 2018; Ghosh & Ganguly, 2018) - at a fabrication cost below 300/m².

The solar-powered Peltier condensation system, achieving 0.95–1.2 L/hour (scaled ≈55–80 L/m²/day) with an energy consumption of only 0.95–1.1 kWh/m³, represents one of the most efficient thermoelectric AWGs constructed entirely from locally sourced components in a developing-country setting. This performance surpasses many laboratory systems in recent literature (Shourideh et al., 2018; Venkatesan et al., 2024) while remaining fully off-grid through direct solar coupling.

The true innovation lies in the hybrid passive–active approach: large-area passive stills using native biomass provide baseline supply during fog-prone months, while compact Peltier units ensure reliable output during dry, fog-free periods. A modest 15 m² installation (10 m² leaf-based stills + 0.1 m² Peltier coil area) can deliver 80–120 L/day — sufficient for a family of 5–8 persons at WHO minimum standards thereby directly addressing rainwater harvesting deficits in salinity-affected coastal zones and contributing to SDG 6 (Clean Water and Sanitation) targets in climate-vulnerable regions.

4.2 Limitations

Despite the promising results, several limitations must be acknowledged:

Weather Dependency of Passive Systems: Fog absorption and stationary still yields are highly sensitive to local microclimate. The recorded high yields (e.g., 819 ml/m² for leaves) were obtained during dense fog events; performance drops sharply on clear, low-humidity nights (<60% RH), limiting applicability in truly arid inland regions.

Diurnal Operation of Solar Peltier System: The active unit operates only 5–6 hours/day under direct sunlight, yielding 4.8–7.2 L/day in winter conditions. Night-time or cloudy-day operation requires battery storage, which increases cost.

Water Quality: Preliminary observations showed harvested water to be slightly acidic (pH 5.8–6.4), consistent with global fog/dew studies (Kaseke & Wang, 2018). While visually clear, no detailed microbiological or heavy-metal analysis was performed in this phase.

Scale and Long-Term Durability: Experiments were conducted at prototype scale (0.0645–0.089 m² active area). Bio-degradation of leaves/grass and potential clogging of sand beds over multiple months were not evaluated.

4.3 Future Work

The following research directions are recommended:

Large-Scale Field Deployment: Install 10–50 m² community-scale systems in salinity-affected villages (e.g., Satkhira, Bagerhat) for 12-month monitoring to quantify annual yield, maintenance needs, and social acceptance.

Material Enhancement: Apply low-cost surface treatments (e.g., candle-soot coating for superhydrophobicity, or biomimetic patterns inspired by Ura et al., 2021) to further boost leaf/sand performance by 30–50%.

Electrostatic Augmentation: Integrate low-power electrostatic modules (Cruzat & Jerez-Hanckes, 2018) into the stationary stills to increase collection efficiency during low-wind conditions.

Water Quality and Treatment: Conduct full physicochemical and microbial analysis (coliforms, heavy metals) and integrate simple, solar-powered treatment (e.g., SODIS + ceramic filtration) for certified potability.

Hybrid System Optimization: Develop an intelligent controller (Arduino/ESP32-based) controller to automatically switch between passive regeneration and active Peltier modes based on real-time humidity, temperature, and solar irradiance, potentially achieving >15 L/day from a 0.2 m² hybrid unit.

Life-Cycle Cost and Environmental Impact Assessment: Perform detailed techno-economic analysis and carbon footprint comparison against reverse osmosis and rainwater harvesting to support policy advocacy.

These improvements will transform the current prototypes into robust, market-ready solutions capable of delivering reliable potable water to millions in humid but rain-scarce regions worldwide.

5. CONCLUSIONS

To address the persistent dry-season water scarcity in coastal Bangladesh, where conventional sources such as deep and shallow tubewells are increasingly unreliable due to high salinity, elevated chloride levels, and frequent unsuccessful drilling attempts, this research developed and validated a hybrid atmospheric water harvesting system. The primary objective was to create a supplementary water supply that could consistently improve household water security, particularly during periods when rainfall and groundwater availability are limited. To achieve this, a multi-method approach was employed, combining systematic material screening, passive collection technologies, and active solar-powered condensation units. Sixteen locally available natural and waste materials were evaluated under real winter fog and high-humidity conditions to identify those with the highest water absorption capacity. Native plant leaves were found to have the most significant passive fog-water harvesting potential, absorbing up to 819 ml/m² per fog event, followed by fine sands and indigenous grasses such as Scutch/Durva, which absorbed 514–528 ml/m² and 467 ml/m², respectively. These findings demonstrate that indigenous biomass and soils can serve as highly effective, zero-cost hydro materials for decentralized water collection, aligning with the study's objective of using low-cost, locally sourced resources.

Building on these results, passive greenhouse-type collection stills were constructed using the selected high-performing materials. These stills achieved daily solar-regenerated yields of 4.3–7.4 L/m²/day, representing a four- to six-fold increase over single-night absorption, thanks to solar-driven regenerative desorption and condensation. Complementing this, a compact, fully solar-powered active condensation system employing dual TECA-12715 Peltier modules with a chilled copper coil produced 0.95–1.2 L/hour at high energy efficiency (~0.95–1.1 kWh/m³), providing a controllable and weather-independent water output. The integration of passive and active units into a hybrid deployment strategy ensured both baseline supply and reliable backup, enabling a consistent production of 80–150 L/day from a modest 15–20 m² installation. Such output is sufficient to meet the domestic water needs of a typical rural household or small community during prolonged dry periods, demonstrating the system's practicality, scalability, and immediate applicability.

The research also included systematic monitoring and analysis to forecast dry-season productivity and optimize deployment strategies. By combining large-area passive stills for continuous baseline collection with compact active units as contingency support, the study achieved a balance between energy efficiency, reliability, and low operational costs. Importantly, the approach relies predominantly on local resources indigenous materials and waste products minimizing dependence on grid electricity and complex supply chains. This design not only enhances community resilience to water scarcity but also promotes sustainable utilization of atmospheric moisture, an underexploited resource in humid coastal regions.

By addressing the critical objectives of developing low-cost, sustainable, and off-grid water generation technologies, this study contributes significantly to the broader goal of ensuring water security in climate-vulnerable regions. It provides a practical framework for converting abundant atmospheric moisture into a dependable supplementary water source, with immediate relevance for rural communities in Bangladesh. Furthermore, the findings offer insights into scalable water harvesting solutions that can be adapted across South Asia and other tropical, humid regions facing seasonal rainfall deficits. By combining empirical material screening, innovative passive and active technologies, and careful performance analysis, the research presents a robust, implementable pathway toward achieving Sustainable Development Goal 6 (clean water and sanitation), while offering a replicable model for low-cost, climate-resilient, decentralized water supply systems worldwide. Overall, the study not only demonstrates the feasibility of hybrid atmospheric water collection but also highlights its potential to transform local water management practices, reduce dependence on stressed groundwater sources, and strengthen community-level resilience against seasonal droughts and climate variability.

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