

Comparative Evaluation of Facade-Based Water Harvesting Technologies for Sustainable Buildings in India's Arid Climate

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Abstract: *India's arid and semi-arid regions, including the Thar Desert, Kutch, and Marwar tracts, are experiencing accelerating groundwater depletion, with national assessments indicating that a majority of monitored wells show declining levels [1]. While rooftop rainwater harvesting is widely implemented and mandated by several state governments, the vertical building envelope remains a comparatively unexploited water-harvesting surface, despite its large exposed area in dense urban settings. This paper undertakes a comparative evaluation of facade-integrated water harvesting approaches, namely fog harvesting, dew and passive radiative condensation, sorption-based atmospheric water generation, and biomimetic surface enhancement, assessed alongside traditional and contemporary vertical rainwater channeling. A multi-criteria comparative framework is constructed from published technical performance, climatic suitability, architectural integration, and cost data, and applied to representative Indian arid climate zones. It is found that dew-based radiative condensation shows the strongest evidence base for Indian conditions, given documented field trials in Gujarat, while sorption-based atmospheric water generation, though still emerging at building scale, is best suited to the very low relative humidity conditions typical of interior arid tracts. Fog harvesting is found to be climatically restricted to coastal or orographic-fog locations, and vertical rainwater channeling, informed by vernacular precedent, is found to remain the most cost-effective and technically mature option. A technology-selection framework linked to micro-climatic zoning is proposed for architects and building planners.*

Keywords: facade water harvesting, atmospheric water harvesting, arid climate, sustainable buildings, building envelope, dew harvesting, India

1. Introduction

Water scarcity across India's arid and semi-arid regions has intensified in recent decades. According to the Composite Water Management Index published by NITI Aayog, groundwater levels declined at a rate of 10 to 25 millimetres per year between 2002 and 2016, and 54 percent of monitored groundwater wells nationally were found to be in decline [1]. It is reported that the extraction rate for the country as a whole reached 63 percent of annually replenishable recharge by 2017, with several states, including Rajasthan, Punjab, and Haryana, exceeding the 70 percent threshold considered safe [1]. Global assessments similarly indicate that freshwater withdrawal relative to available resources has been rising steadily, placing water-stressed countries such as India at heightened long-term risk [19].

Building-integrated rainwater harvesting from rooftops is comparatively well established in India, with several states, including Tamil Nadu, having made rooftop rainwater harvesting structures compulsory under municipal building bye-laws [18]. The vertical building envelope, however, has received far less research and design attention as a water-harvesting surface. In dense urban contexts, particularly in mid- and high-rise construction, the exposed facade area of a building frequently exceeds its roof area by a considerable margin, suggesting unrealized potential for supplementary water capture.

Internationally, several facade-based water harvesting mechanisms have been investigated, including fog interception through mesh-covered double-skin facades [2, 3, 4], dew formation through passive nocturnal radiative cooling [6, 7], sorption-based atmospheric water generation using porous hygroscopic materials [15], and biomimetic surface

treatments inspired by desert organisms [16]. Much of this research has, however, been undertaken in coastal fog belts, Mediterranean islands, or laboratory settings, with comparatively limited attention paid to India's specific combination of climatic conditions, namely high daytime temperatures, low winter humidity across the interior desert tracts, and seasonally concentrated monsoon rainfall.

This paper aims to address this gap by comparatively evaluating facade-based water harvesting technologies for India's arid climate. The objectives of the study are: to review the technical principles and reported performance of the major facade-based water harvesting mechanisms; to assess their climatic suitability against India's arid and semi-arid zones; to develop a multi-criteria comparative framework incorporating technical, climatic, architectural, and economic factors; and to derive a technology-selection framework of practical use to architects and building professionals.

2. Climatic and Hydrological Context of India's Arid and Semi-Arid Regions

India's arid zone, corresponding broadly to the Koppen BWh classification, is concentrated in western Rajasthan, including the Thar Desert, and in Kutch and parts of Saurashtra in Gujarat, while a wider semi-arid BSh belt extends across the Deccan plateau and parts of central India. These regions are characterized by low and highly seasonal rainfall, concentrated within the monsoon months of June to September, combined with high summer temperatures and, in several tracts, elevated nocturnal relative humidity arising from proximity to coastal or marshland areas such as the Rann of Kutch.

The suitability of a given facade-based water harvesting technology is strongly dependent on this local climatic profile. Fog harvesting requires either advective coastal fog or orographic fog formation, conditions found in only limited parts of India; most documented facade or building-based fog harvesting demonstrations internationally have occurred in locations with frequent, dense fog events, a condition largely absent across the Indian interior arid tracts [2]. Dew and passive radiative condensation, in contrast, depend on clear night skies, low wind speeds, and moderate relative humidity, conditions commonly present in Gujarat's coastal-influenced arid zone; documented dew-collection field trials at Kothara and in the Kutch area confirm that such conditions recur through much of the year in this specific micro-region [12, 13]. Sorption-based atmospheric water generation is comparatively less climate-restricted, as certain hygroscopic sorbents, including metal-organic frameworks, have been shown to capture water even at relative humidity levels as low as 10 to 20 percent, extending applicability to the drier interior tracts of Rajasthan [15]. Vertical rainwater channeling depends primarily on monsoon rainfall intensity and is therefore seasonally concentrated but broadly applicable across the entire arid and semi-arid belt.

3. Literature Review

3.1 Facade-Integrated Fog Harvesting

The systematic proposal to treat building envelopes as fog-harvesting devices, rather than relying solely on freestanding large fog collectors, is generally credited to Caldas et al., who proposed that ventilated double-skin facades could be designed to intercept airborne fog droplets and channel collected water into storage reservoirs [2]. A subsequent study by the same research group reported experimental results using radiative condenser surfaces, cooled below ambient temperature at night to induce additional condensation, as a complementary element within such water-harvesting facades [3]. Building on this line of research, Di Bitonto, Kutlu, and Zanelli proposed a smart facade concept employing modular textile mesh panels capable of simultaneously providing fog-water harvesting and solar shading functions, an approach intended to improve the economic case for facade-integrated fog systems by combining water and energy benefits within a single building element [4]. Earlier foundational work on fog collection efficiency using large mesh-based collectors established much of the basic design methodology later adapted to building envelopes [5]; more recent design proposals have continued to expand the range of architectural applications for fog-harvesting textiles [20].

Despite this progress, facade-mounted fog harvesting remains constrained by climatic dependency on frequent fog events, together with practical challenges including mesh maintenance, dust accumulation, and material degradation under prolonged ultraviolet exposure, all of which necessitate durable, self-cleaning, and corrosion-resistant coatings for long-term operation.

3.2 Dew and Passive Radiative Condensation Systems

Dew harvesting exploits the passive radiative cooling of a surface below the dew-point temperature of the surrounding air during clear nights, causing atmospheric water vapor to condense directly onto the surface. Foundational experimental work established that an inexpensive radiative condenser, constructed using titanium dioxide and barium sulphate microspheres embedded in a polyethylene foil, could achieve measurable nightly water yields when optimized for high long-wave emissivity, low solar absorption, and efficient droplet drainage [6]. Subsequent multi-year comparative trials using large inclined radiative condensers demonstrated variable but consistent dew yields across different structural configurations, with a theoretical maximum yield in the region of 0.8 litres per square metre per day under favourable conditions [7].

Of particular relevance to this study, dew-collection field trials have been conducted directly within India. A study of dew water yields on galvanized-iron roofs at Kothara, in north-west India, recorded measurable dew accumulation over a multi-month observation period during the dry season [12]. A subsequent, considerably larger installation, an 850-square-metre ridge-type dew and rain collector in the Kutch area of Gujarat, was monitored over an extended multi-year period and confirmed that meaningful water yields could be achieved at a scale relevant to institutional or community water supply, while also validating water quality against national and World Health Organization drinking-water standards [13]. These India-specific trials, though rooftop- or ground-mounted rather than facade-integrated, provide the strongest available evidence base for the climatic viability of radiative dew condensation within an Indian arid context.

Complementary studies from other dry and coastal-arid regions worldwide, including measurement and modelling work across island, coastal, and alpine locations [8], grassland sites in temperate Europe [10], the Dalmatian coast of Croatia [11], and early Scandinavian trials [9], collectively demonstrate that dew yields are highly sensitive to condenser material emissivity, wind exposure, and surface inclination, findings directly transferable to the design of facade-mounted dew condensers. A wider critical review of dew as a non-conventional water resource has further consolidated these findings, concluding that although individual yields remain modest, dew represents a reliable supplementary water source in locations where it occurs frequently and where more conventional sources are constrained [14].

3.3 Sorption-Based Atmospheric Water Harvesting

Sorption-based atmospheric water harvesting extracts moisture from air using porous hygroscopic materials that adsorb water vapor and subsequently release it as liquid water upon mild heating, commonly using solar thermal energy. Metal-organic frameworks have emerged as a particularly promising class of sorbent material, owing to their tunable pore chemistry and their capacity to capture water even under the low relative-humidity conditions characteristic of desert environments [15]. Specific metal-organic-framework variants have been shown capable of capturing atmospheric water at relative humidity levels as low as 10 to 20 percent, a

range consistent with conditions found in India's interior arid tracts during much of the dry season.

While sorption-based systems have been extensively validated at laboratory and small-device scale, building-integrated deployment, for example as solar-regenerated sorption panels mounted on or within a facade cavity, remains comparatively immature, and reported energy requirements for the regeneration cycle continue to constrain large-scale adoption. This technology is therefore best characterized, within the present comparative framework, as an emerging rather than a currently mature option for Indian facade applications.

3.4 Biomimetic Surface Strategies

Alongside mechanism-specific technologies, biomimetic surface treatments have been investigated as a means of enhancing the water-collection efficiency of both fog and dew harvesting facades. The water-collection mechanism of the Namib Desert beetle, in which alternating hydrophilic and hydrophobic regions on the insect's dorsal surface promote droplet nucleation, coalescence, and directed drainage, was elucidated in a widely cited foundational study and has since become the principal biological reference point for bio-inspired water-harvesting surface design [16]. Architectural applications of this principle have subsequently been explored, applying similar hydrophilic-hydrophobic surface patterning to building cladding and shading elements in order to improve droplet capture and directed drainage toward collection channels.

Within the present comparative framework, biomimetic surface patterning is best understood as a material-level performance enhancement applicable across both the fog-harvesting and dew-harvesting categories described above, rather than as an independent, freestanding technology category.

3.5 Vertical Rainwater Channeling and Traditional Precedents

India possesses a long-standing tradition of rainwater harvesting adapted to arid and semi-arid conditions. In the semi-arid regions of Rajasthan, houses have traditionally incorporated underground storage tanks connected by pipework to sloped rooftops, with the initial rainfall of a monsoon event conventionally discarded to clear accumulated dust from the roof and pipe surfaces before subsequent rainfall was collected and stored. This vernacular practice illustrates the long-established architectural logic of using the building envelope, including sloped roof surfaces functioning in effect as a facade extension, as a primary water-collecting element well before contemporary facade-based terminology was introduced.

Contemporary Indian policy has extended this tradition into mandatory building regulation. Tamil Nadu, for example, has required rooftop rainwater harvesting structures to be incorporated into building plans under municipal law, a measure credited with measurable improvement in groundwater recharge in the state [18]. Site-suitability assessment for rainwater harvesting has also increasingly

employed multi-criteria geospatial methods, integrating rainfall, slope, soil, land cover, and drainage density data within a weighted decision framework, a methodological precedent directly relevant to the comparative framework developed later in this paper.

3.6 Multi-Criteria Comparative Evaluation Methods

Facade design is widely recognized as a multi-disciplinary problem involving several, frequently conflicting, performance criteria, including structural, thermal, and, increasingly, water-harvesting considerations; this complexity has driven the development of systematic multi-criteria decision-making procedures within facade engineering research, ranging from simple weighted-scoring matrices to advanced computational optimization methods [17]. Such methods provide a directly transferable precedent for the construction of a comparative evaluation framework capable of ranking facade-based water harvesting technologies against one another using multiple, weighted criteria.

4. Research Gap and Objectives

Despite the range of technologies reviewed above, no published study has yet undertaken a systematic, India-specific, facade-scale comparative evaluation of fog harvesting, dew and radiative condensation, sorption-based atmospheric water generation, and vertical rainwater channeling using a consistent set of technical, climatic, architectural, and economic criteria. Existing India-specific field data, including the Kothara and Kutch dew trials [12, 13], are valuable but rooftop- or ground-mounted rather than facade-integrated, while fog and sorption research relevant to arid climates has been undertaken predominantly outside India. This paper addresses this gap by constructing an explicit comparative framework, populated with the best available published performance data, and applying it to representative Indian arid climate conditions.

5. Methodology

5.1 Comparative Evaluation Framework

A multi-criteria comparative framework was developed to permit consistent evaluation of four candidate technology categories: fog harvesting, dew and radiative condensation, sorption-based atmospheric water generation, and vertical rainwater channeling. The framework structure was informed by established multi-criteria facade-design methodology [17].

5.2 Evaluation Criteria

Five criteria groups were defined for the comparative evaluation. Technical performance was assessed using reported water yield per unit collecting area, and sensitivity to relative humidity, fog frequency, or clear-sky nights. Climatic compatibility was assessed against India's arid-zone climatic sub-types identified in Section 2. Architectural integration was assessed in terms of compatibility with facade orientation, shading co-benefit, structural loading, and maintenance access. Economic feasibility was assessed using approximate capital and maintenance cost, informed by

reported project costs where available. Technology readiness was assessed in terms of the maturity of building-scale deployment, distinguishing established, pilot-tested, and laboratory-stage technologies.

5.3 Data Sources

Performance, cost, and climatic-suitability data were compiled from the peer-reviewed literature reviewed in Section 3, supplemented by policy and technical reports addressing Indian water resource conditions [1, 18]. Because primary facade-scale field data specific to India remain limited, the comparative evaluation in Section 6 draws on the closest available analogues, principally rooftop- and ground-mounted Indian dew trials [12, 13] and international facade-

scale fog and sorption studies. This extrapolation is treated as an explicit limitation of the present study, discussed further in Section 7.

6. Comparative Results

6.1 Technology Performance Summary

Table 1 summarizes the reported technical performance, climatic dependency, architectural integration characteristics, approximate cost bracket, and technology readiness level of the four candidate facade-based water harvesting categories, based on the literature reviewed in Section 3.

Table 1: Comparative Summary of Facade-Based Water Harvesting Technologies

Technology	Working Principle	Reported Yield	Climatic Requirement	Cost Level	Technology Readiness
Fog Harvesting	Mesh interception of fog droplets on facade [2, 4]	Variable; fog-frequency dependent	Frequent coastal or orographic fog	Low to Moderate	Pilot Stage
Dew / Radiative Condensation	Nocturnal radiative cooling below dew point [6, 7]	Up to approximately 0.8 L/m ² /day [7]	Clear night sky, low wind, moderate humidity	Low	Field-Validated in India [12, 13]
Sorption-Based Atmospheric Water Generation	Hygroscopic sorbent adsorption and solar desorption [15]	Material-dependent; laboratory scale	Effective even at 10-20% relative humidity	High	Laboratory / Emerging
Vertical Rainwater Channeling	Facade/roof-directed monsoon runoff to storage	Site- and rainfall-dependent	Seasonal monsoon rainfall	Low	Established / Mandated [18]

6.2 Climatic Suitability Mapping

When mapped against the climatic sub-zones described in Section 2, dew and radiative condensation show the strongest documented suitability for Gujarat's coastal-influenced arid tract, consistent with the Kothara and Kutch field trial locations [12, 13]. Sorption-based atmospheric water generation shows the broadest theoretical applicability across India's arid zone, including the drier interior tracts of Rajasthan, owing to its comparatively lower relative-humidity threshold [15], though building-scale validation specific to Indian conditions remains absent from the reviewed literature. Fog harvesting shows the narrowest climatic applicability within India, being realistically restricted to locations with a demonstrable fog climatology, a condition not characteristic of the majority of India's arid interior. Vertical rainwater channeling remains broadly applicable across the full arid and semi-arid belt, constrained primarily by the seasonal concentration of monsoon rainfall rather than by daily or nightly climatic variation.

6.3 Weighted Comparative Ranking

Applying approximately equal weighting across the five criteria groups defined in Section 5.2, vertical rainwater channeling is found to rank highest overall, reflecting its technical maturity, comparatively low cost, and broad climatic applicability, consistent with its long-standing vernacular precedent in Rajasthan and its current regulatory support [18]. Dew and radiative condensation is found to rank second, supported by direct Indian field evidence [12, 13], though constrained to specific micro-climatic conditions. Fog harvesting and sorption-based atmospheric water generation are found to rank lower under present conditions, the former due to narrow climatic applicability within India and the latter

due to low technology readiness at building scale, though sorption-based systems may be expected to improve in relative ranking as sorbent materials and solar-regeneration integration mature.

7. Discussion

7.1 Architectural Design Implications

The comparative results suggest that a hybrid design approach, rather than reliance on a single technology, is likely to be most effective for Indian arid-climate buildings. A double-skin facade combining a shading mesh layer with an integrated dew-condensing rear surface, for example, could plausibly combine the established shading and energy-performance benefits of double-skin facades with the specific climatic suitability of dew condensation demonstrated in Gujarat.

7.2 Policy Implications

Given the existing regulatory precedent for rooftop rainwater harvesting in states such as Tamil Nadu, extending building codes to recognize facade-integrated water harvesting, particularly dew condensation in climatically suitable regions, represents a comparatively low-cost policy intervention with a demonstrated technical basis [18].

7.3 Limitations

The principal limitation of this study is the scarcity of facade-scale, as opposed to rooftop- or ground-scale, field data specific to Indian conditions, particularly for fog harvesting and sorption-based atmospheric water generation. The comparative rankings presented in Section 6 should

accordingly be understood as indicative, pending primary facade-scale pilot studies or building-performance simulation specific to Indian climatic conditions.

8. Conclusion

This paper has undertaken a comparative evaluation of four facade-based water harvesting technology categories for application in India's arid and semi-arid climate. Dew and passive radiative condensation systems are found to present the strongest documented evidence base for Indian conditions, supported by direct field trials in Gujarat, while sorption-based atmospheric water generation, though climatically promising for India's drier interior tracts, remains at an early stage of building-scale technology readiness. Fog harvesting is found to be climatically restricted to limited coastal or orographic-fog locations within India, and vertical rainwater channeling, informed by long-standing vernacular precedent, is found to remain the most technically mature and cost-effective option overall. A hybrid facade approach combining shading, dew condensation, and conventional rainwater channeling is proposed as the most promising direction for future Indian sustainable building practice. It is recommended that future research prioritize facade-scale field trials and building-performance simulation specific to India's diverse arid and semi-arid micro-climates.

Conflict of Interest

No conflict of interest is associated with this research. The study was not sponsored, and no external organization influenced the findings presented.

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