

Air-to-Water Condensation Farming and Fogponics for "Zero-Watering" Horticulture in India: A Review of Technologies, Crop Suitability and Readiness for El Niño-Driven Water Scarcity

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Abstract— India produced an estimated 369.05 million tonnes of horticultural produce from 29.48 million ha in 2024–25. Its per-capita water availability, however, has fallen to about 1,486 m³ (2021) and is projected to reach 1,367 m³ by 2031, below the 1,700 m³ water-stress threshold. Greenhouse warming is expected to strengthen the inverse El Niño–monsoon relationship. Future El Niño years may therefore cause crop-yield losses about 30% larger than those observed historically, and nearly 200 Indian districts have been identified as highly vulnerable in 2026. This review examines two complementary pathways that decouple high-value horticulture from rainfall and groundwater: (i) air-to-water condensation farming, in which atmospheric water generators (AWGs), sorbent-based harvesters, dew condensers or fog collectors, preferably solar-powered, supply condensate to the root zone of sheltered crops; and (ii) fogponics, an aeroponic variant that delivers nutrient solution as a 5–30 µm fog to suspended roots. Published evidence shows that solar-driven atmospheric water can irrigate leafy vegetables with growth comparable to tap water, that fog collectors can yield 2.9–3.3 L m⁻² day⁻¹ (annual mean) at favourable coastal sites, and that aeroponic seed-potato systems are commercially established in India. Specific energy demand nevertheless ranges from about 0.02 kWh L⁻¹ in humid air to 3.64 kWh L⁻¹ in very dry air, and levelized water costs of US\$ 0.09–0.40 L⁻¹ have been reported. These figures confine the approach, at present, to high-value, small-footprint protected cultivation, nurseries and propagation. A crop-suitability matrix for Indian fruits, vegetables and flowers, an agro-climatic zoning framework, a sizing procedure and a research roadmap are proposed. "Zero watering" is best understood as zero dependence on irrigation from surface or groundwater, not zero water input. The technology can serve as climate-insurance infrastructure for nurseries and protected horticulture during El Niño years.

Keywords— Atmospheric water generator, Fogponics, Aeroponics, Protected cultivation, El Niño, Water scarcity, Solar energy, Indian horticulture.

I. INTRODUCTION

Horticulture is the fastest-growing segment of Indian agriculture. The Third Advance Estimates for 2024–25 place total horticultural production at 369.05 million tonnes from 29.48 million ha, about 4% higher than the previous year [1]. This output is grown on a shrinking water base. The Ministry of Jal Shakti reports that average annual per-capita water availability fell to 1,486 m³ in 2021 and will decline to 1,367 m³ by 2031; availability below 1,700 m³ is classed as water-stressed [2]. Groundwater, the backbone of horticultural irrigation in peninsular and north-western India, is already heavily used. Most fruit, vegetable and flower crops in rainfed or semi-irrigated tracts are highly sensitive to the timing and quantity of monsoon rainfall.

The El Niño–Southern Oscillation (ENSO) adds a recurrent shock to this structural scarcity. In June 2026 the USDA Foreign Agricultural Service reported that India was moving from ENSO-neutral conditions towards El Niño. The India Meteorological Department expected El Niño to influence the July–September monsoon, and the Government of India had identified nearly 200 districts as highly vulnerable to El Niño-related agricultural impacts [3]. Zhao et al. [4] showed that greenhouse warming

strengthens rather than weakens the inverse ENSO–Indian summer monsoon rainfall relationship. Their constrained projections indicate that monsoon sensitivity to ENSO could be nearly 40% greater than historical levels, and that crop-yield losses in El Niño years could be about 30% larger than in the past. Horticulture therefore needs water sources that do not depend on the monsoon.

The atmosphere is one such source. Even in dry seasons, the air above Indian farms holds water vapour. Two families of technology can deliver this vapour to plants. Air-to-water condensation farming uses atmospheric water generators (AWGs), sorbent-based harvesters, radiative dew condensers or fog nets to produce liquid water, ideally powered by solar photovoltaics (PV), and supplies it to the root zone of crops grown under shelter. Fogponics, a variant of aeroponics, delivers water and nutrients to suspended roots as a fine fog of 5–30 μm droplets [5], minimising the volume of water a crop needs. Combined in a closed protected structure that also recaptures crop transpiration, the two approaches underpin the idea of "zero-watering" horticulture, meaning cultivation with no irrigation drawn from wells, canals or tanks.

Most research on these technologies addresses drinking water, space farming or materials science. It has rarely been synthesized for Indian horticultural crops or framed as an El Niño adaptation. This review aims to (i) explain the physical principles and technology options; (ii) summarize the experimental evidence on crop production with atmospheric water and fog-based root nutrition; (iii) assess the suitability of major Indian fruits, vegetables and flowers; (iv) propose an agro-climatic deployment framework and sizing procedure for India; and (v) critically discuss energy, cost and hygiene limits and outline a research and policy roadmap. A conceptual mind map of the review is shown in Fig. 1.



FIGURE 1: Mind map of zero-watering horticulture based on air-to-water condensation farming and fogponics, covering principles, technologies, delivery, crop groups, Indian agro-climatic zones and constraints.

II. METHODOLOGY OF THE REVIEW

This is a narrative, evidence-based review. Literature was identified through web and scholarly searches (Google Scholar, ScienceDirect, MDPI, Nature Portfolio, ACS Publications and ISHS Acta Horticulturae) and Government of India and international agency portals (Ministry of Agriculture & Farmers Welfare, Ministry of Jal Shakti/PIB, NITI Aayog, ICAR and USDA FAS). Search strings combined the terms atmospheric water generator, atmospheric water harvesting, sorbent, hydrogel, metal–organic framework, dew, fog collection, fogponics, aeroponics, ultrasonic fogger, minituber, protected cultivation, El Niño and India. Priority was given to peer-reviewed studies from 2018–2026 that report quantitative crop, water-yield, energy or cost outcomes, and to official statistics for the Indian context. Where a quantitative value is quoted, the original source is cited. Crop-suitability ratings and zoning recommendations are the author's synthesis of the reviewed evidence and established horticultural practice, and are presented as hypotheses for field validation rather than tested results.

III. PHYSICAL PRINCIPLES OF HARVESTING WATER FROM AIR

3.1 Psychrometric basis

Water vapour condenses on a surface cooled below the dew-point temperature (T_d) of the surrounding air. The closer T_d is to air temperature (i.e., the higher the relative humidity, RH), the less cooling is needed per litre. The harvestable quantity, however, is governed by absolute humidity, so hot and humid air (coastal India, the monsoon season) holds far more extractable water than cool or dry air. Diurnally, RH is highest at night and before dawn, when air temperature is lowest. This is why passive dew condensers and sorbent systems run their capture phase at night.

3.2 Energy floor

Condensing water releases its latent heat of vaporisation (about 2.45 MJ kg^{-1} at ambient temperature). Removing this heat therefore requires at least about $0.68 \text{ kWh per litre}$ ($2.45 \text{ MJ} \div 3.6 \text{ MJ kWh}^{-1}$), before compressor, fan and heat-exchanger losses. Practical systems can use less electricity than this only where the thermodynamic work is shifted to free energy sources such as solar heat for sorbent regeneration or radiative sky cooling. A recent comprehensive review reported specific energy consumption from about 0.02 kWh L^{-1} under high-humidity conditions to 3.64 kWh L^{-1} in very low-humidity environments [6]. Machine-level reviews quote about 3 kWh L^{-1} for a vapour-compression unit producing 14 L day^{-1} [7]. Climate is thus the single largest determinant of feasibility.

3.3 Closed-loop water recapture

In an enclosed growing space, most water supplied to plants is transpired back to the air. A dehumidifying condenser inside a sealed polyhouse or container farm can recover this vapour and return it to the nutrient tank. This makes the structure partly self-sustaining, so that the AWG has to supply only the net water fixed in biomass and lost through leakage. This recapture concept is central to realistic zero-watering designs (Fig. 2).

IV. AIR-TO-WATER TECHNOLOGIES FOR CROP PRODUCTION

TABLE 1
COMPARISON OF AIR-TO-WATER TECHNOLOGIES RELEVANT TO HORTICULTURE

Technology	Working principle	Best climate	Energy input	Reported performance (source)	Horticultural fit
Refrigerative (vapour-compression) AWG	Coil cooled below T_d by a compressor; condensate collected	Warm, humid (RH > ~60%)	Electricity (grid or solar PV)	~3 kWh L ⁻¹ for a 14 L day ⁻¹ unit [7]; 0.02–3.64 kWh L ⁻¹ across humidity range [6]	Polyhouse supplementary water; nursery misting; fogponic tanks in coastal/NE India
Sorbent-based AWH (MOF, hydrogel, hygroscopic salt gels)	Night-time vapour sorption; daytime solar-heated desorption and condensation	Semi-arid to arid	Mostly solar heat; low electricity	Off-grid solar system irrigated Chinese cabbage with growth comparable to tap water [8]; arid-climate solar-desiccant AWH: levelized water cost US\$ 0.09–0.40 L ⁻¹ depending on power source [9]	Drip/wick supply for containers and small polyhouses in Deccan and Thar
Soil-applied hygroscopic gels/aerogels	Gel captures vapour and releases it in the root zone	Dry, sandy soils	Passive	PAM–chitosan–CaCl ₂ aerogel extended ryegrass survival by 5–12 days at 20–30% RH without irrigation [10]; super-moisture-absorbent gels used for atmospheric water irrigation [11]	Establishment of seedlings and orchard transplants; drought bridging
Passive radiative dew condenser	Surface cooled by night-sky radiation below T_d	Clear, calm, humid nights	None	Low and highly variable output; site-specific	Supplementary water for nurseries and potted plants
Fog nets / mesh collectors	Wind-driven fog droplets intercepted by mesh	Coastal or hill sites with frequent fog	None	2.9–3.3 L m ⁻² day ⁻¹ annual mean at Atacama sites feeding a hydroponic greenhouse [12]; up to ~10 L m ⁻² day ⁻¹ reported at Alto Hospicio [13]	Western Ghats, Nilgiris and NE hill stations

The strongest crop-level evidence comes from Yang et al. [8], who built a stand-alone, maintenance-free solar-driven atmospheric water extraction (SAWE) system for off-grid irrigation. Chinese cabbage irrigated only with harvested atmospheric water showed growth, soil volumetric water content and electrical conductivity comparable to plants irrigated with tap water. This demonstrates that condensate is agronomically adequate when supplied to the root zone. Alborno et al. [12] linked fog collectors to a hydroponic greenhouse in the Atacama Desert and recorded annual mean fog-water yields of 2.9 and 3.3 L m⁻² day⁻¹ at two sites, showing that fog-fed soilless horticulture is technically possible in a hyper-arid region. Li et al. [14] estimated that an AWH installation of 25 kW with a water-uptake efficiency of 3.33 L kWh⁻¹ could meet substantial agricultural demand in suitable humid regions, underlining the role of climate. The techno-economic analysis by Gayoso et al. [9] reported a levelized cost of water of US\$0.17 L⁻¹ with grid power, US\$0.17 L⁻¹ with grid power, US\$ 0.40 L⁻¹ with newly purchased off-grid PV and US\$ 0.09 L⁻¹ with existing PV in an arid climate. These costs are orders of magnitude above conventional irrigation water and are only justifiable for high-value crops, nurseries or emergencies.

V. FOGPONICS: PRINCIPLES AND EVIDENCE

5.1 Concept

Aeroponics grows plants with roots suspended in a dark chamber and periodically sprayed with nutrient solution. Fogponics replaces the spray with a continuous or pulsed fog produced by ultrasonic transducers or high-pressure nozzles. Fog emitters generate droplets of about 5–30 μm , finer than the 30–100 μm droplets typical of high-pressure aeroponics [5, 15]. Very fine droplets remain suspended, coat fine roots and root hairs, and keep the root zone highly aerated. Liquid water use is minimal because nearly all the fog either contacts roots or condenses and drains back to the reservoir. The approach is independent of soil quality and weather, and has been coupled with IoT sensing and fuzzy-logic control of temperature, humidity and pH [5].

5.2 Crop evidence

Aeroponics is already commercial in Indian seed-potato production. ICAR–Central Potato Research Institute, Shimla, perfected an aeroponic minituber technology in 2011 and has licensed it to private firms [16, 17]. Elsewhere, optimised aeroponic systems have produced an average of 491 minitubers per plant [15]. In leafy vegetables, comparisons of aeroponic, hydroponic and substrate culture of lettuce indicate that aeroponics promotes root development and yields comparable to or higher than conventional soilless systems [18]. Dry-fog application has also been tested in strawberry under protected cultivation [19]. Reviews note fogponics studies on potato and system development for red chilli in aeroponic greenhouses [5]. Evidence for perennial fruit crops is restricted to propagation (rooting of cuttings, seedlings and micro-plants), where high humidity and root aeration are already routine.

5.3 Limitations specific to fogponics

- Fog is so fine that heavier nutrient ions and dissolved calcium may be delivered less efficiently than in coarser aeroponic sprays. Nutrient strength and fogging cycles must be calibrated.
- Ultrasonic transducers warm the solution and form mineral scale. Discs need regular cleaning or replacement, and condensate (low in minerals) reduces scaling.
- Roots have no water buffer. A fogger or power failure can desiccate roots within hours, so battery or UPS backup and humidity alarms are essential.
- Warm, humid chambers favour biofilm and pathogens. Disinfection (UV/ozone), tank shading and temperature control are mandatory.

VI. INTEGRATED SYSTEM DESIGN

Fig. 2 shows an integrated design. Solar PV with battery storage powers a refrigerative AWG, a sorbent harvester or both, chosen according to local humidity. Passive dew or fog collectors add free water where conditions allow. Condensate passes through sediment filtration and UV/ozone disinfection into an opaque, shaded tank. Because condensate is nearly free of minerals, a fertigation unit doses a complete nutrient solution including Ca, Mg and micronutrients, and controls EC and pH. Water is delivered either as nutrient fog to a fogponic root chamber (leafy greens, strawberry, orchids, minitubers, nursery) or by subsurface drip, wick or container systems (tomato, capsicum, cut flowers, fruit nurseries). The protected structure, whether a polyhouse, net house or container farm, contains a dehumidifier that recaptures transpired water and chamber run-off. An IoT controller monitors RH, temperature, vapour-pressure deficit (VPD), tank level, EC, pH and root-zone moisture, and schedules AWG operation for the most humid hours.

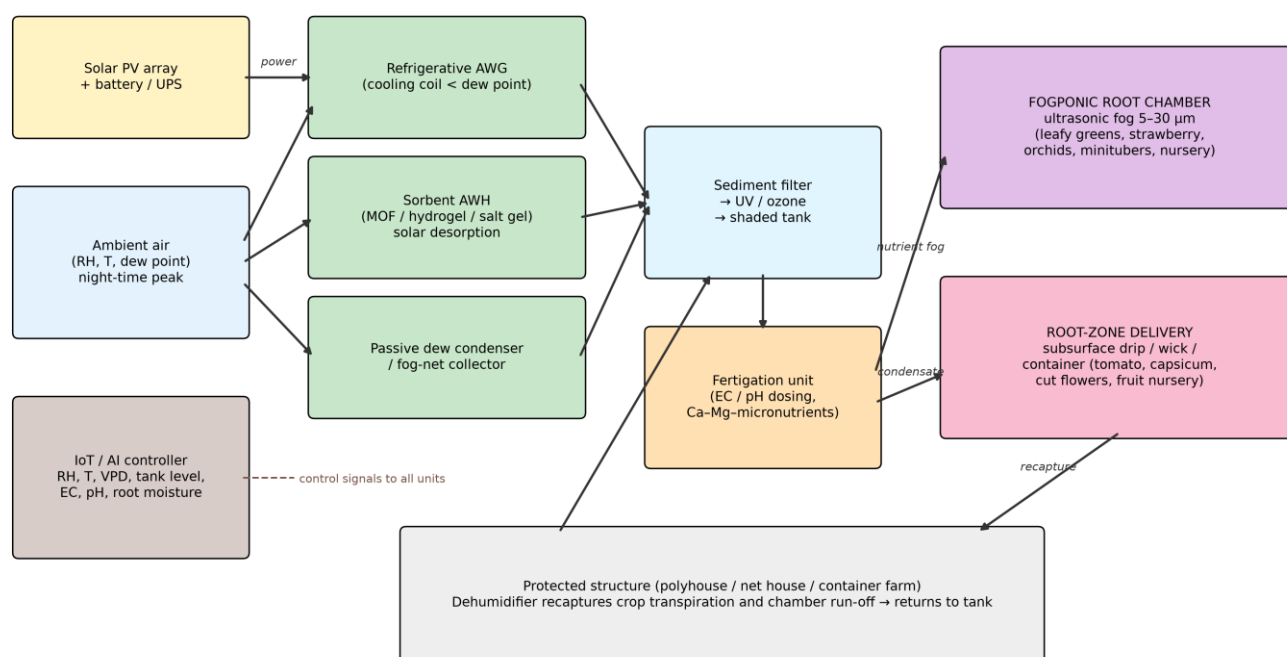


FIGURE 2: Schematic of a solar-powered air-to-water condensation and fogponic system for zero-watering protected horticulture (author's conceptual design).

TABLE 2
INDICATIVE NUTRIENT-SOLUTION AND ENVIRONMENTAL TARGETS FOR CONDENSATE-BASED SOILLESS CULTURE (TO BE CALIBRATED PER CULTIVAR AND LOCATION)

Parameter	Leafy vegetables & herbs	Strawberry	Tomato / capsicum / cucumber	Cut flowers (gerbera, carnation, rose)	Remarks
EC (dS m ⁻¹)	~1.0–1.8	~1.0–1.5	~2.0–3.5	~1.2–2.0	Condensate EC is near zero; all nutrients must be added
pH	5.5–6.5	5.5–6.2	5.5–6.5	5.5–6.2	Low buffering of condensate; monitor daily
Fog/spray cycle	Continuous low fog or short pulses	Pulsed	Drip / wick preferred	Drip or fog in propagation	Adjust to root-chamber RH
Root-zone temperature	Below ~25 °C	Below ~22–24 °C	Below ~26 °C	Below ~24 °C	Shading and evaporative cooling in Indian summers
Hygiene	UV/ozone; weekly cleaning	Same	Same	Same	Biofilm and Legionella risk in warm stagnant water

Note: Table 2 values are working ranges compiled from common soilless-culture practice, not from a single trial. They must be validated for Indian cultivars under condensate-fed systems.

VII. CROP SUITABILITY FOR INDIAN HORTICULTURE

Crop suitability depends on water demand per unit area, economic value per litre of water, root-zone tolerance of soilless culture and duration in the system. Table 3 synthesises the reviewed evidence into a suitability matrix for Indian conditions.

TABLE 3
SUITABILITY OF INDIAN HORTICULTURAL CROPS FOR AIR-TO-WATER CONDENSATION FARMING AND FOGPONICS (AUTHOR'S SYNTHESIS)

Crop group	Crops	Recommended mode	Suitability	Rationale / evidence
Leafy vegetables & herbs	Lettuce, spinach, amaranth, coriander, fenugreek, basil, mint, microgreens	Fogponics / aeroponics	★★★ High	Short cycle, small plants, high value per litre; aeroponic lettuce performs as well as or better than hydroponics [18]; atmospheric water adequate for leafy brassica [8]
Tuber seed production	Potato minitubers	Aeroponics / fogponics	★★★ High	Commercial ICAR–CPRI aeroponic technology [16, 17]; high minituber numbers per plant [15]
Fruiting vegetables	Cherry tomato, capsicum, cucumber, chilli	Condensate drip / wick in polyhouse; fog in nursery	★★ Moderate	Higher water demand and plant size; suited where AWG output is high (coastal/NE) or as drought back-up
Soft fruits	Strawberry (day-neutral)	Fogponics / vertical aeroponics; condensate drip	★★★ High	Compact, high-value; dry-fog strawberry trials [19]
Fruit crop propagation	Mango, citrus, guava, pomegranate, papaya, fig, dragon fruit, grapes (cuttings, seedlings, grafts)	Fog chamber for rooting and hardening; then drip	★★★ High (nursery stage)	High humidity and aeration accelerate rooting; small water volume per plant; adult trees not feasible
Orchard trees	Mango, citrus, guava, banana (adult)	Not recommended (only hydrogel establishment aid)	★ Low	Water demand far exceeds AWG output; aerogels can bridge transplant drought [10, 11]
Cut flowers	Gerbera, carnation, chrysanthemum, rose	Condensate drip in polyhouse; fog for propagation	★★ Moderate	High value per stem; established soilless protocols
Epiphytic and pot flowers	Orchids (Dendrobium, Phalaenopsis), anthurium, bedding plugs	Fogponics / fog-humidified benches	★★★ High	Aerial roots adapted to humid air; low water demand

VIII. AGRO-CLIMATIC DEPLOYMENT FRAMEWORK AND SIZING FOR INDIA

8.1 Zoning

Because energy per litre is governed mainly by absolute humidity [6], deployment should follow India's humidity gradients. Table 4 proposes a first-order zoning, which must be refined with at least one year of local hourly RH and temperature data from IMD or automatic weather stations before investment.

TABLE 4
PROPOSED AGRO-CLIMATIC DEPLOYMENT FRAMEWORK FOR AIR-TO-WATER HORTICULTURE IN INDIA
(AUTHOR'S PROPOSAL)

Zone (examples)	Humidity regime	Preferred technology	Priority crops / uses
Coastal belts (Kerala, Konkan, coastal Andhra Pradesh and Tamil Nadu, West Bengal); North-East	High RH most of the year	Refrigerative AWG on solar PV; closed-loop polyhouses	Leafy greens, strawberry, orchids, anthurium, nurseries
Western Ghats, Nilgiris, NE hill stations	Frequent seasonal fog	Fog nets + storage; AWG as back-up	Nurseries, cut flowers, potato minitubers
Deccan plateau (Telangana, interior Karnataka, Maharashtra, Andhra Pradesh)	Humid in monsoon, dry in summer	Hybrid: AWG + sorbent AWH + rainwater tank; transpiration recapture	Fruit-crop nurseries, vegetable seedlings, high-value protected crops during El Niño years
Arid north-west (Thar, Kutch) and cold arid Ladakh	Very low RH	Sorbent AWH, dew condensers, sealed container farms only	Microgreens, herbs and seedlings for local markets and defence/remote stations

8.2 Sizing procedure

A simple sizing chain is recommended: (1) daily water requirement W ($L \text{ day}^{-1}$) = per-plant water use $\times$ number of plants, reduced by the recapture fraction in sealed structures; (2) derated generator output = rated $L \text{ day}^{-1} \times$ local RH/temperature derating factor taken from the manufacturer's performance curve; (3) daily energy E (kWh) = $W \times$ specific energy ($kWh \text{ L}^{-1}$) at local conditions; (4) PV capacity (kWp) $\approx E \div$ (peak sun hours $\times$ system efficiency). As an illustration only, a system needing $200 L \text{ day}^{-1}$ at $0.5 kWh \text{ L}^{-1}$ requires $100 kWh \text{ day}^{-1}$. With 5 peak sun hours and 75% system efficiency, this needs about 27 kWp of PV. The same requirement at $3 kWh \text{ L}^{-1}$ (dry air) would need about 160 kWp , which shows why humid zones, closed-loop recapture and low-demand crops are essential.

IX. ROLE UNDER EL NIÑO AND CLIMATE CHANGE

El Niño typically weakens the south-west monsoon, reducing rainfall for rainfed kharif crops and increasing heat stress and irrigation demand [3]. As warming intensifies the ENSO–monsoon link [4], horticulture will face sharper and more frequent supply shocks. Air-to-water systems will not replace the monsoon for field horticulture. They can, however, serve as climate-insurance infrastructure in three ways: (i) keeping nurseries and planting-material production running in drought years, which protects the next season's orchard and vegetable establishment; (ii) sustaining high-value protected crops (leafy greens, strawberry, flowers) near urban markets; and (iii) producing disease-free seed potato and propagules in aeroponic/fogponic units. Because AWG output rises with humidity, these systems also complement rather than compete with rainwater harvesting. Tanks fill during monsoon surpluses, and AWGs add water during humid but rain-deficient spells, which are common in El Niño monsoons.

X. CONSTRAINTS AND CRITICAL APPRAISAL

- **Energy and cost:** $0.02\text{--}3.64 kWh \text{ L}^{-1}$ depending on humidity [6] and levelized costs of US\$ $0.09\text{--}0.40 \text{ L}^{-1}$ [9] restrict the approach to high-value, small-area systems.
- **Low output in hot, dry periods:** in Indian summers the demand for water peaks just when AWG output is lowest. Sorbent systems and night-time operation only partly mitigate this.
- **Capital and maintenance:** compressors, fans, filters, ultrasonic discs and sensors need skilled maintenance that is scarce in rural areas.
- **Water quality and hygiene:** condensate lacks minerals and can carry airborne contaminants. Warm tanks risk biofilm and Legionella, so filtration, UV/ozone and complete fertigation are mandatory.
- **Evidence gaps:** few replicated trials exist on Indian cultivars, and no long-term economic or life-cycle assessments for condensate-fed horticulture were found.

- **Terminology:** "zero watering" should be communicated as zero irrigation from surface or groundwater. The system still consumes water from the air and significant energy.

XI. RESEARCH AND POLICY ROADMAP

TABLE 5
RESEARCH AND POLICY PRIORITIES

Horizon	Research priorities	Policy and extension
Short term (1–3 years)	Replicated trials of condensate-fed leafy vegetables, strawberry and fruit nurseries in coastal, Deccan and arid zones; cultivar-specific EC/pH and fog-cycle protocols; humidity-mapping for AWG suitability	Pilot units at horticultural universities and KVKs; inclusion of solar AWG–fogponic units under protected-cultivation subsidies
Medium term (3–5 years)	Hybrid AWG–sorbent systems; transpiration-recapture greenhouses; AI scheduling for peak-humidity operation; life-cycle and economic analyses	Bundling with agrivoltaics and PM-KUSUM solar schemes; farmer-producer-organization-run nursery hubs
Long term (> 5 years)	Low-cost MOF/hydrogel sorbents made in India; drought-resilient nursery networks; integration with El Niño early-warning systems	National standards for condensate quality in horticulture; El Niño contingency plans that include protected nursery capacity

XII. CONCLUSION

Air-to-water condensation farming and fogponics together offer a technically proven way to grow selected horticultural crops without drawing on rainfall, rivers or groundwater. Crop-level evidence confirms that atmospheric water can sustain leafy vegetables, that fog collection can feed greenhouse hydroponics, and that aeroponic seed-potato production is commercially established in India. The decisive constraint is energy per litre, which depends strongly on humidity. Current deployment is therefore rational mainly for nurseries, propagation, seed potato, leafy greens, strawberry and flowers in humid or foggy zones, and as climate-insurance infrastructure during El Niño years. With closed-loop recapture, solar integration, India-specific trials and supportive policy, "zero-watering" protected horticulture can become a practical part of India's adaptation to declining water availability and a strengthening El Niño threat.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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