NullLabs

Passive Airwell Irrigation System

Business Plan, Technical Specification, and Installation Guide

A fully passive, zero-energy water harvesting and irrigation system using radiative dew condensers, buried cisterns, honeycomb subsurface dripline, and mycorrhizal biome scaffolding.

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Reference Site	Fort Collins, CO (5,000 ft / 1,530 m)
Comparison Site	Decatur, GA (1,000 ft / 305 m)
Target Climate	Semi-arid to humid subtropical

Contents

1. Executive Summary

This document describes a fully passive water harvesting, irrigation, and soil biome restoration system that requires zero energy input and has no moving parts. The system chains proven technologies into a novel integrated configuration: a radiative dew condenser feeding a buried cistern, with collected water distributed through a subsurface honeycomb dripline lattice designed to scaffold mycorrhizal fungal network formation.

Two condenser designs are presented. **Design A (Radiative Cooling)** uses a lightweight, high-emissivity panel tilted at 30 degrees that radiates infrared heat to the cold night sky through the 8-13 micrometer atmospheric transparency window. The surface cools 6-8 degrees C below ambient without any connection to ground thermal mass. Field data from sites worldwide show yields of 0.1-0.4 L/m2 on productive nights (roughly 45% of nights in semi-arid climates). **Design B (Ground-Coupled Air Loop)** draws ambient air through buried pipes where it cools below the dew point, and condensate collects at the low point. This requires passive wind-driven intake and is better suited to humid climates.

The key innovation is not the water collection method (both are well-documented) but the **integration of the dripline geometry with soil biome development**. The honeycomb subsurface lattice delivers zero-nutrient condensate water at consistent moisture levels, creating conditions that strongly promote arbuscular mycorrhizal fungal colonization. The lattice geometry provides a spatial scaffold for underground fungal network formation. Over 2-3 years, the system bootstraps a self-sustaining plant-fungal ecosystem that can survive on natural precipitation alone — the irrigation infrastructure is scaffolding, not permanent life support.

> **System summary:** Radiative panel condenses atmospheric moisture. Condensate drains into a buried cistern. Cistern gravity-feeds a honeycomb subsurface dripline. The dripline delivers zero-nutrient water that promotes mycorrhizal dependency. The honeycomb geometry templates underground fungal network formation. The water is the vehicle; the biome is the payload.

An optional self-powered smart valve, using thermoelectric generation from the cistern's ground-to-surface temperature differential, provides soil-moisture-responsive irrigation control with zero external power input.

2. Business Plan

2.1 Value Proposition

This system does not compete with municipal water on cost. Its value lies in providing vegetation establishment and soil biome restoration where conventional water supply is unavailable, unreliable, or prohibitively expensive to install.

- **Fully passive** — zero energy, zero moving parts, zero operating cost.
- **Infrastructure-independent** — works where there is no water hookup, no electricity, and insufficient rainfall for rain harvesting.
- **Self-sustaining** — once installed, requires no ongoing input. No consumables, no filters, no degradation of core components.
- **Biome-building** — the system is designed to make itself obsolete. Once mycorrhizal networks establish and vegetation matures (2-3 years), the plants can survive on natural precipitation.
- **Incrementally scalable** — add units and extend the lattice without redesigning the system.

2.2 Target Markets

The system is best suited for applications where water access is the binding constraint:

Segment	Need	Scale
Off-grid homesteads	Supplemental irrigation without well or utility	5-20 units
Land restoration / reforestation	Establish vegetation on arid unserviced land	50-500 units
Desert permaculture	Passive water source for food forests	10-50 units
Dryland soil rehabilitation	Rebuild mycorrhizal networks in degraded soils	20-200 units
Emergency / humanitarian	Water in disaster zones with no power	Modular kits

2.3 Unit Economics

Bill of materials per unit (radiative panel + cistern share):

Component	Full Retail	Salvage
High-emissivity foil (2 sq m)	$10-20	$5-10

Panel frame (angled support)	$15-30	$10-15
Gutter + drain fitting	$10-15	$5-10
Cistern allocation (HDPE drum)	$40-60	$20-30
Dripline share (per unit)	$10-15	$10-15
Jute wrapping for dripline	$5-10	$3-5
Mycorrhizal inoculant (per unit)	$5-10	$5-10
Misc (fittings, sealant)	$10-15	$5-10
Total per unit	$105-175	$63-105

2.4 Array Configurations

System yield depends on climate, humidity, and sky conditions. Based on OPUR field data (Muselli et al., 478 days in Corsica), passive radiative condensers in semi-arid climates produce ~0.12 L/m2 on productive nights, with roughly 45% of nights being productive. The all-nights season average is ~0.05 L/m2/night.

The critical metric is the **collection-to-irrigation area ratio**: how many square meters of panel are needed per square meter of irrigated garden.

Plant Type	Water Need	Panel Ratio (FC)	Panel Ratio (Decatur)
Xeriscaping / native	1.5 L/m2/week	4.3 : 1	~1.5 : 1 *
Drought-tolerant	3.0 L/m2/week	8.6 : 1	~3 : 1 *
Vegetable garden	6.0 L/m2/week	17 : 1	~6 : 1 *

*Water need figures are mid-range estimates; actual needs vary by species, soil, and microclimate. * Decatur estimates are less well-documented.*

What this means in practice

In Fort Collins, irrigating 10 m2 of xeriscaping requires roughly 43 m2 of panel area — the equivalent of a modest roof or fence-line installation. However, the system's primary value is biome establishment, not permanent irrigation. After 2-3 growing seasons with mycorrhizal network support, established native plants can typically survive on natural precipitation alone.

Garden Size	Xeriscaping	Drought-Tolerant
5 m2 (small bed)	22 m2 panel, $1,100-$1,700	43 m2 panel, $2,200-$3,400

10 m2 (garden row)	43 m2 panel, $2,200-$3,400	86 m2 panel, $4,300-$6,900
25 m2 (plot)	107 m2 panel, $5,400-$8,600	Not practical as sole source

> **Honest framing:** This system is not a replacement for municipal water. In Fort Collins, it is a biome bootstrapping system for establishing small areas of native plants on sites with no water infrastructure. The panels can be distributed across rooftops, fence lines, and unused slopes. In humid climates like Decatur, ratios are 3-5x more favorable.

2.5 Competitive Landscape

System	Energy	Water Source	Op. Cost	Biome Building
This system	None	Humidity	None	Yes (designed for it)
Fog nets	None	Fog only	Net replacement	No
Rain barrels	None	Rainfall	None	No
Solar pump + well	Solar	Groundwater	Maintenance	No
Municipal water	Grid	Utility	Monthly bill	No

No other system combines passive water harvesting with deliberate mycorrhizal network scaffolding. This is the unique niche: not just delivering water, but building the soil biology that makes water delivery eventually unnecessary.

3. Technical Specification

3.1 System Overview

The system comprises four subsystems, all driven by gravity and passive physics:

- **Condensing surface** — a tilted, high-emissivity panel that radiates infrared heat to the cold night sky through the 8-13 micrometer atmospheric window. Cools 6-8 degrees C below ambient. Condensate drains by gravity into the cistern.
- **Cistern** — a buried vessel at 2-3m depth, at stable ground temperature (~10-12 degrees C in Fort Collins). Provides water storage and thermal differential for optional Seebeck generation.
- **Dripline lattice** — a subsurface honeycomb drip network, gravity-fed from the cistern. Jute-wrapped tubing provides slow-release carbon source for soil microbiota.
- **Biome layer** — mycorrhizal inoculant applied at installation, promoted by zero-nutrient water delivery and no-till permanence. The lattice geometry templates fungal network formation.

> **Design philosophy:** Every stage uses gravity or passive physics. The water collection is the vehicle; the mycorrhizal biome scaffolding is the payload. The system is designed to make itself obsolete within 2-3 growing seasons.

3.2 Cistern

Parameter	Value	Notes
Depth (center)	2.0 - 3.0 m	Below frost line, stable temp zone
Volume (minimum)	2,000 L	Per unit or shared
Ground temperature	~10-12 C (Fort Collins)	Varies by region; measure locally
Material	Concrete / HDPE / ferrocement	Waterproof, durable
Thermal capacity	8.36 MJ/K (at 2,000 L)	Increases with fill level

3.3 Altitude and Pressure Effects

At Fort Collins elevation (~5,000 ft / 1,530 m), atmospheric pressure is approximately 84 kPa — 83% of sea-level pressure.

Solar irradiance

The thinner atmosphere transmits approximately 8-12% more total solar irradiance than at sea level (UV specifically increases ~15-20%). Fort Collins receives ~10.7 hours of sunshine per day in July. Orient panels with a slight north-facing bias to reduce direct solar exposure.

Radiative cooling efficiency

Lower absolute humidity at altitude means the 8-13 micrometer atmospheric window is more transparent. The condensing panel radiates heat to the sky more efficiently.

Parameter	Sea Level	Fort Collins
Atmospheric pressure	101.3 kPa	~84 kPa
Atm. window transparency	Baseline	Improved
Solar irradiance (total)	Baseline	+8-12%
UV intensity	Baseline	+15-20%
Net effect on dew yield	Baseline	Mixed (better cooling, less moisture)

3.4 Condensing Surface

Parameter	Value

Surface area	2.0 sq m per unit
Geometry	30-degree tilted panel with gutter
Material	High-emissivity PE or PETG foil on insulated frame
Cooling mechanism	Radiative emission through 8-13 um window
Cooling power	25-100 W/m2 (clear night sky)
Temp. reduction	6-8 C below ambient (near-blackbody emitter)

3.5 Subsurface Dripline Lattice

The dripline uses a honeycomb geometry decomposed into three sets of parallel trenches at 60-degree angles, matching standard trenching equipment.

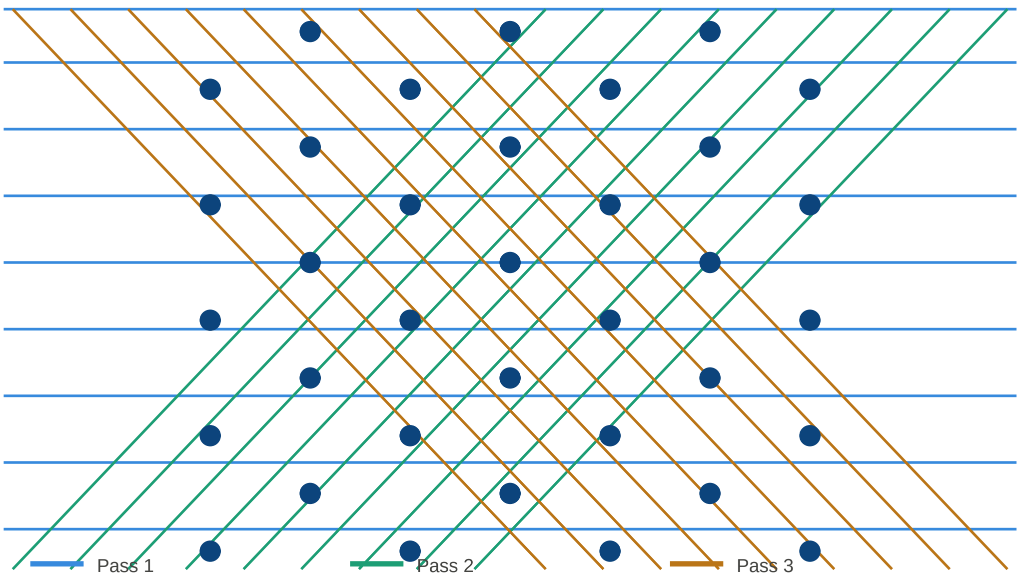

Figure 1: Three-pass trenching pattern. Intersections form hex lattice; dots show unit positions.

Parameter	Value
Emitter spacing	70 cm along each line
Hex row spacing	~61 cm between parallel lines
Trench depth	15 - 30 cm
Material	Drip tubing with jute wrapping

Feed pressure	Gravity from cistern

3.6 Performance Modeling

Performance depends on the relationship between the radiative-cooled surface temperature and the nighttime dew point. The panel cools approximately 6-8 degrees C below ambient. Parameters are based on OPUR field data adapted for Fort Collins.

Condition	Value
Night air temp (July avg low)	~15 C (Fort Collins)
Radiative cooling reduction	6-8 C below ambient
Achievable surface temp	~7-9 C
Documented yield (semi-arid)	0.10-0.15 L/m2 per productive night
Productive night frequency	~45% of nights (Corsica field data)
All-nights season average	~0.05 L/m2/night
Yield per unit (2 m2 panel)	~0.10 L/unit/night (season avg)
Monthly yield per unit	~3 L/month

> **Key constraint:** Radiative cooling achieves 6-8 degrees C below ambient on clear nights. In Fort Collins (July lows ~15 degrees C), the panel reaches ~7-9 degrees C. Condensation occurs when this drops below the dew point. Dry nights (dew point 3-6 degrees C) are productive. Humid post-storm evenings (dew point >10 degrees C) are not, because clouds also block the IR window.

3.7 Humidity Sensitivity

Night air temperature 15 degrees C. Radiative cooling achieves ~7 degrees C below ambient, giving surface temperature ~8 degrees C.

Night RH	Dew Point	Margin	Yield/m2/night	Assessment
25%	-4.9 C	12.9 C	0.50 L	Excellent
35%	-0.3 C	8.3 C	0.43 L	Excellent
45%	3.2 C	4.8 C	0.25 L	Good
55%	6.0 C	2.0 C	0.05 L	Marginal
65%	8.5 C	-0.5 C	0.00 L	No condensation
75%	10.6 C	-2.6 C	0.00 L	No condensation

3.8 Fort Collins Site Assessment

Parameter	Value	Impact
Elevation	5,000 ft (1,530 m)	Improved radiative efficiency
Station pressure	~84 kPa	More transparent atm. window
Ground temp (2.5 m)	~10-12 C	Good for TEG
July avg high / low	31 C / 15 C	Strong day-night delta (~16 C)
Summer avg RH	~45-48%	Moderate (good dew margin)
Summer dew points	5-8 C typical	Below panel surface temp
Annual sunshine	~300 days	Excellent for radiative cooling
Monsoon (Jul-Sep)	9+ rain days/month	Natural supplement

Honest assessment: Fort Collins is at the marginal end for total yield, but the low humidity is favorable for radiative cooling efficiency. Best suited as supplemental irrigation for xeriscaping during the establishment phase. The mycorrhizal network building is the primary long-term value.

3.9 Decatur, GA Comparison Site

Parameter	Fort Collins, CO	Decatur, GA
Elevation	5,000 ft	1,000 ft
July avg high / low	31 C / 15 C	33 C / 22 C
Summer avg RH	~45%	~69-74%
Summer dew points	5-8 C	18-22 C
Ground temp (2.5 m)	~10-12 C	~16-18 C
Best collection method	Design A (radiative)	Design B (earth tube)
Primary constraint	Low humidity	Cloud cover / airflow

Key insight: Fort Collins and Decatur require opposite collection strategies but the same storage, distribution, and biome scaffolding layers. The cistern, dripline lattice, mycorrhizal inoculation, and smart valve are universal across climates.

4. Alternative Collection Configurations

This section evaluates passive mechanisms for cooling a condensing surface below the dew point. The optimal method depends on local humidity and sky conditions.

4.1 Radiative Sky Cooling (Design A)

Earth's atmosphere has a transparency window at 8-13 micrometers that coincides with peak thermal radiation of ambient-temperature surfaces. A sky-facing surface with high emissivity in this band radiates heat directly to outer space, cooling itself 6-8 degrees C below ambient. Documented yields: 0.1-0.4 L/m2/productive night. Material cost under $10/m2.

> **Verdict: PRIMARY RECOMMENDATION.** Proven, cheap, simple. Best for dry, clear-sky climates.

4.2 Ground-Coupled Air Loop (Design B)

Ambient air drawn through buried pipes at 1.5-3 m depth cools to ground temperature. If the air's dew point exceeds ground temperature, moisture condenses. Best for humid climates where dew points regularly exceed 16-18 degrees C.

> **Verdict: SUPPLEMENTARY.** Best for humid climates (Decatur). Marginal at Fort Collins humidity.

4.3 Massive Thermal Inertia

Historical approach (Zibold condenser, Chaptal pyramid). Modern analysis shows massive structures underperform lightweight radiative panels because thermal inertia prevents rapid cooling below the dew point.

> **Verdict: NOT RECOMMENDED.** Outperformed by lightweight panels.

4.4 Desiccant Sorption/Desorption

Hygroscopic materials absorb moisture at night, solar heat regenerates during the day. Works at any humidity including below 30% RH. MIT demonstrated a passive window-sized panel. More complex than radiative panels but the only approach for very arid conditions (<30% RH).

> **Verdict: PROMISING FOR FUTURE ITERATION.** Phase 2 enhancement.

4.5 Recommended: Hybrid Radiative + Cistern

The recommended system:

- **Collection:** Tilted high-emissivity foil panels, ~2 m2 each, at 30 degrees slope.
- **Storage:** Buried cistern at 2-3m depth.
- **Distribution:** Honeycomb subsurface dripline with jute wrapping.
- **Biome:** Mycorrhizal inoculant at installation. Zero-nutrient water maintains fungal dependency.
- **Control:** Optional self-powered smart valve (Section 5).

5. Self-Powered Instrumentation (Seebeck)

The buried cistern creates a persistent temperature differential between cool underground water (~10-12 degrees C) and warm surface (~30+ degrees C on summer days). This can be harvested via the Seebeck effect to power sensors and actuators.

5.1 Thermoelectric Generation

Parameter	Value
Seebeck coefficient (Bi2Te3)	~200-250 uV/K per couple
Standard TEG module	~127 couples, 40 x 40 mm
Voltage at Delta-T = 20 C	~500-630 mV per module
Power at Delta-T = 20 C	~20-40 mW per module
Module cost	$3-8 each

5.2 Power Budget

Application	Power	Modules	Feasible?
Soil moisture sensor	~0.1 mW	1	Yes
MCU (ATtiny/MSP430)	~0.5-3 mW	1	Yes
Latching solenoid valve	~200 mW (pulsed)	1 + supercap	Yes
Small DC fan	~1000 mW	50+	No

5.3 Smart Dripline Control

One TEG module on the cistern lid feeds a boost converter (LTC3108, operates from 20 mV) charging a supercapacitor. An MCU reads a soil moisture sensor every 15-30 minutes and pulses a latching solenoid valve. Self-regulating: hotter days produce more TEG power, which is when soil dries fastest.

Component	Cost
TEG module	$5
Boost converter (LTC3108)	$3
Supercapacitor (1F, 5.5V)	$2

MCU (ATtiny85)	$2-4
Soil moisture sensor	$3-5
Latching solenoid	$8-15
Thermal paste + hardware	$3
Total	$26-37

6. Mycorrhizal Biome Scaffolding

This section describes the system's most novel aspect: the deliberate use of irrigation geometry, water chemistry, and material selection to scaffold underground mycorrhizal fungal network formation. The water collection and delivery system is the vehicle; the soil biome is the payload.

6.1 The Biome as Payload

Degraded drylands lose not only their vegetation but their soil microbiome. Research on desertification recovery has shown that without functional mycorrhizal networks, replanted vegetation fails even when watered. Requena et al. (2001) demonstrated in long-term Mediterranean experiments that inoculation with indigenous arbuscular mycorrhizal fungi and rhizobial nitrogen-fixing bacteria not only enhanced plant establishment but also increased soil fertility and quality. A review in Science (Coban et al., 2022) identified mycorrhizal fungi, nitrogen-fixing bacteria, and plant growth-promoting rhizobacteria as the most valuable microbial groups for dryland soil restoration.

This system is designed from the ground up to create the conditions these organisms need. Every design decision — water chemistry, delivery geometry, material selection, and operational pattern — is oriented toward mycorrhizal network promotion.

6.2 Factors Promoting Mycorrhizal Colonization

The peer-reviewed literature identifies six primary factors that promote arbuscular mycorrhizal (AM) fungal colonization. This system addresses all six:

Factor	What Research Shows	This System
Consistent moisture	SDI promotes higher AM colonization than furrow irrigation (13.6% vs 10.8%)	Subsurface drip at consistent low flow
Low phosphorus	High soluble P reduces colonization; plants restrict fungi when P is abundant	Zero-nutrient condensate forces mycorrhizal dependency
Soil pH 6.0-7.5	Elevating pH increases AM colonization and total fungal biomass	Condensate (pH ~5.5-6.0) gently acidifies alkaline soils
Minimal disturbance	Tillage decreases AM diversity up to 40%; hyphae exist in top 10-15 cm	One-time trench install; permanent no-till thereafter
Organic carbon source	Organic matter supports fungal growth and soil structure	Jute-wrapped dripline provides slow-release C
Host plant diversity	Different plants host different fungi; polyculture supports diversity	Xeriscaping polyculture recommended at installation

6.3 Honeycomb Geometry as Fungal Network Template

Mycorrhizal hyphae follow moisture gradients in soil. The honeycomb dripline lattice creates a network of connected moisture zones at emitter intersections. Each intersection becomes a node where plant roots concentrate (drawn to the water source), and fungal hyphae bridge between nodes along the moisture channels connecting them. The lattice geometry provides a spatial scaffold that templates underground fungal network development onto the same honeycomb pattern as the dripline.

Research on mycorrhizal networks in water-stressed environments supports this mechanism. Simard's work demonstrated that mycorrhizal network potential increases seedling survival, and this facilitation increases as water stress increases. Water transfer via networks may play a role in this facilitation. The dripline lattice creates precisely the geometry that enables this: discrete moisture nodes connected by soil corridors where hyphae can bridge.

> **Novel claim:** No published research has tested whether a deliberate irrigation geometry can template mycorrhizal network formation. This is the system's most speculative and most potentially significant aspect. A field trial measuring both water yield and root colonization rates at lattice nodes vs. interstitial soil would validate or refute this.

6.4 Jute Fiber as Carbon Source

Wrapping the dripline tubing in jute fiber provides a slow-release organic carbon source at the exact depth where roots and fungi concentrate (15-30 cm). Research on biodegradable mulches shows that soil organic carbon content is higher under jute mulches, and jute improves soil nutrient dynamics including organic matter, nitrogen, phosphorus, and potassium. The jute decomposes over 1-3 years, providing a sustained carbon input to the soil food web during the critical establishment phase.

6.5 Zero-Nutrient Water and Mycorrhizal Dependency

Condensate water from radiative panels is essentially distilled — zero dissolved nutrients, zero phosphorus, zero nitrogen. This is not a limitation but a feature. The literature is clear that high soluble phosphorus reduces mycorrhizal colonization because plants restrict fungal access when phosphorus is freely available. By delivering nutrient-free water, the system forces plants into mycorrhizal dependency for phosphorus acquisition — exactly the symbiotic relationship needed for long-term plant survival after the irrigation system is no longer needed.

This creates a positive feedback cascade: mycorrhizal inoculant establishes → fungi recruit P-solubilizing bacteria → bacteria promote more mycorrhizal establishment → deeper root colonization → more soil organic carbon → improved soil structure and water retention. The zero-nutrient water keeps this cycle running because the plants never get 'lazy' phosphorus from irrigation.

6.6 Dryland Restoration Integration

The system maps directly onto dryland restoration requirements identified in the literature:

- **Establishment phase (Years 1-3):** The system provides supplemental water and mycorrhizal inoculant. Panels deliver condensate; dripline distributes it; jute provides carbon; fungi colonize the lattice geometry.

- **Transition phase (Years 3-5):** Established plants with functional mycorrhizal networks begin accessing soil moisture and mineral nutrients independently. The system provides decreasing supplemental water as plant root systems deepen.
- **Self-sustaining phase (Year 5+):** Plants survive on natural precipitation and mycorrhizal-mediated nutrient cycling. Panels can be relocated to new restoration sites. The dripline lattice and cisterns remain as subsurface infrastructure, continuing to provide moisture buffering during extreme drought.

> **The panels are portable; the biome is permanent.** After 3-5 years, the radiative panels can be moved to bootstrap the next site. The underground infrastructure (cisterns, dripline, established mycorrhizal networks) remains as permanent ecological capital. This means the per-site cost is lower than the BOM suggests — the most expensive components (panels, frames) are reusable across multiple restoration cycles.

7. Installation Guide

This guide covers the recommended configuration: radiative cooling panels draining into buried cisterns, with a honeycomb dripline lattice, mycorrhizal inoculation, and optional self-powered smart valve.

7.1 Site Assessment

- **Climate:** Nighttime RH > 30%, day-night delta > 10 degrees C, clear skies.
- **Sky exposure:** Unobstructed sky view for radiative panels.
- **Soil:** Test pH, P levels, and existing mycorrhizal colonization. Low-P soils are ideal.
- **Slope:** Cisterns upslope of planting area for gravity feed.

7.2 Tools and Materials

Per prototype unit

- Post-hole auger (45-60 cm diameter)
- High-emissivity foil: 2 m2
- Panel frame: wood or aluminum angle
- Rain gutter + downspout fitting
- HDPE barrel (200-500 L)
- Drip tubing with jute wrapping
- Mycorrhizal inoculant (native AM species blend)

For array

- Walk-behind trencher (rental)
- Tee and cross fittings for lattice intersections
- Float valve or smart valve assembly (Section 5.3, ~$30)

7.3 Phase 1: Cistern Excavation

Auger to 2.5-3.0 m depth, lower HDPE drum, backfill. Pre-drill inlet and outlet ports.

7.4 Phase 2: Radiative Panel

- 1. Build A-frame to hold foil at 30 degrees, low edge toward cistern.
- 2. Stretch foil taut, attach gutter at low edge.
- 3. Connect gutter to cistern inlet via PVC with positive slope.
- 4. Position with maximum sky exposure, slight north bias.

7.5 Phase 3: Dripline Lattice

Three-pass trenching at 0/60/120 degrees, 20-25 cm depth, 60 cm spacing. Lay jute-wrapped drip tubing, connect at intersections with tee fittings, connect to cistern outlet, pressure test, backfill.

7.6 Phase 4: Mycorrhizal Inoculation

This is a critical step that distinguishes the system from conventional drip irrigation.

- 1. **Source native inoculant:** Use a blend of indigenous AM fungi species, not commercial monocultures. Local soil from healthy native plant communities is ideal as a starter culture.
- 2. **Apply at root depth:** Place inoculant directly at emitter points (lattice intersections) during backfill, at 15-20 cm depth where roots will concentrate.
- 3. **Plant host species:** Install native, highly mycorrhizal-dependent plant species at each lattice node. Polyculture (3-5 species minimum) supports fungal diversity.
- 4. **Avoid fertilizer:** Do not add phosphorus or nitrogen fertilizer. The zero-nutrient water is intentional — it forces mycorrhizal dependency.
- 5. **Add carbon:** If not using jute-wrapped tubing, add a thin layer of compost or leaf litter at installation depth to provide initial carbon for fungal growth.

> **Critical:** The mycorrhizal inoculation must happen at installation time, before backfill. Once the trenches are closed, the soil is undisturbed permanently. The inoculant at lattice nodes seeds the network that will grow along moisture channels between nodes.

7.7 Phase 5: TEG Smart Valve (Optional)

Mount TEG module on cistern lid (black plate on top, cistern contact on bottom). Wire to boost converter, supercapacitor, MCU, soil sensor, and latching solenoid. See Section 5.3.

7.8 Commissioning

- 1. Fill cistern with 100-200 L initial charge.
- 2. Check for condensation on first clear night (>35% RH).
- 3. Measure yield with graduated container at cistern inlet.
- 4. Verify dripline flow at all emitter points.
- 5. After 4-8 weeks: extract small soil samples at lattice nodes and interstitial points. Stain roots and check for mycorrhizal colonization. This is the most important validation metric.

7.9 Scaling to Full Array

- **Trial (2-3 panels, 1 summer):** ~$300-500. Measure water yield AND root colonization rates.
- **Expansion:** Add panels and extend lattice incrementally.

- **Relocation:** After 3-5 years, move panels to new site. Underground biome infrastructure remains.

> **Recommended trial protocol:** Install 2-3 panels, shared cistern, jute-wrapped dripline in a small hex lattice. Plant native xeriscaping at lattice nodes with AM inoculant. Run one summer. Measure: (1) condensation yield per night, (2) soil moisture at nodes vs. interstices, (3) root mycorrhizal colonization at nodes vs. interstices. The colonization comparison is the critical experiment.

8. Experimental Design

The preceding sections describe a system whose individual components are validated but whose integration is untested. This section defines the minimum experiment needed to validate or refute the core claims. The experiment is designed to be inexpensive, completable in one growing season, and to produce unambiguous results on the two questions that matter.

8.1 Hypotheses

The system makes two testable claims. Everything else in this document is either established science or engineering implementation detail.

- **H1 (Water yield):** A 2 m2 radiative PE foil panel tilted at 30 degrees, draining into a buried cistern, will produce a measurable and non-trivial volume of condensate in Fort Collins during June-September. Predicted yield: 0.05-0.15 L/m2 per productive night, with 40-50% of nights productive. This is a replication of existing OPUR data in a new climate; the prediction is conservative.
- **H2 (Biome scaffolding):** Mycorrhizal colonization rates at dripline lattice nodes (emitter points) will be significantly higher than at interstitial points (midway between nodes) after one growing season, when inoculant is applied at nodes and zero-nutrient condensate is delivered via the lattice. This is the novel claim. No prior work has tested whether irrigation geometry templates fungal network topology.

> **H1 is a calibration experiment.** If it fails, the climate is unsuitable and the system should be trialed elsewhere. **H2 is the discovery experiment.** If it succeeds, it establishes a new mechanism for directed biome construction.

8.2 Test Matrix

Three treatment groups, minimum 3 replicates each:

Group	Dripline	Water Source	Inoculant	Purpose
A: Full system	Hex lattice (jute-wrapped)	Condensate (zero-nutrient)	AM blend at nodes	Test H1 + H2
B: Water control	Hex lattice (jute-wrapped)	Tap water (has nutrients)	AM blend at nodes	Isolate nutrient effect on AM
C: Geometry control	Random emitter placement	Condensate (zero-nutrient)	AM blend (broadcast)	Isolate geometry effect on AM

Group A tests the full system. Group B tests whether zero-nutrient water matters (vs. tap). Group C tests whether lattice geometry matters (vs. random placement).

An optional fourth group (D: no irrigation, inoculant only) would establish the baseline colonization rate for the site without any supplemental water. If resources are limited, drop Group D first, then Group B. Groups A and C are the minimum viable experiment for testing H2.

8.3 Trial Layout

Each replicate occupies a 2 x 2 m plot (4 m2). Groups are spatially randomized with at least 2 m buffer between plots to prevent underground moisture cross-contamination. Total footprint: 9-12 plots at 4 m2 each = 36-48 m2 of ground, plus panel area.

- **Group A plots:** Hex dripline with 3 nodes per plot (emitters at 70 cm spacing). One radiative panel (2 m2) per plot, draining into a shared or individual 200 L cistern. AM inoculant placed at each node during installation. Three native xeriscaping species planted at nodes.
- **Group B plots:** Identical layout to Group A, but cistern is filled manually with tap water on the same schedule as Group A's measured condensate yield. This controls for water chemistry while holding geometry and inoculant constant.
- **Group C plots:** Same total dripline length and emitter count, but emitters placed randomly (not on a hex grid). Same condensate water source. AM inoculant broadcast evenly over the plot rather than concentrated at emitter points. Plants placed at emitter locations.

8.4 Measurements and Instrumentation

Primary measurements

- **Condensate yield (H1):** Graduated collection vessel at each cistern inlet, read daily at dawn. Record alongside nighttime low temperature, RH (cheap DHT22 sensor or weather station), wind speed, and sky condition (clear/partly cloudy/overcast).
- **Mycorrhizal colonization (H2):** At weeks 8, 16, and end-of-season: extract root samples from (a) lattice nodes (within 5 cm of emitter), and (b) interstitial points (midway between nodes, 35 cm from nearest emitter). Clear and stain roots (trypan blue or ink-vinegar method). Quantify colonization by the gridline intersect method. Report as percentage of root length colonized.

Secondary measurements

- **Soil moisture:** Capacitive sensors at 2-3 nodes and 2-3 interstices per plot. Log hourly. Cheap option: Teros 10 or generic capacitive probes.
- **Plant survival and growth:** Height, leaf count, canopy diameter at weeks 4, 8, 12, 16, end-of-season.
- **Soil chemistry:** pH and plant-available P (Olsen P) at start and end of season, at node and interstitial positions.
- **Panel surface temperature:** IR thermometer readings at 2 AM on 3-5 representative nights to verify radiative cooling magnitude.

Optional (if budget allows)

- **Hyphal density mapping:** Soil cores at nodes, interstices, and along the dripline path between nodes. Quantify extraradical hyphal density to test whether hyphae follow the moisture channels between nodes.
- **TEG voltage logging:** If smart valve is installed, log TEG output voltage and soil moisture over the season to validate the self-powered feedback model.

8.5 Controls

The experimental design controls for the following confounds:

Confound	Controlled By
Water chemistry (nutrients in tap vs. condensate)	Group B receives tap water, same geometry
Geometry (hex lattice vs. random placement)	Group C uses random emitter layout
Microclimate variation across plots	Spatial randomization of groups
Natural rainfall diluting treatment effects	All groups receive same rainfall; measure cistern-only yield separately
Pre-existing soil mycorrhizal community	Baseline colonization measured at T=0 across all plots
Inoculant placement vs. broadcast	Group A: point-applied at nodes. Group C: broadcast

8.6 Timeline

Phase	When	Duration	Activities
Site prep	Late May	1 week	Soil testing, plot layout, baseline samples
Installation	Early June	1 week	Cisterns, panels, dripline, inoculant, planting
Monitoring	June - Sept	16 weeks	Daily yield, weekly plant checks, soil moisture logging
Mid-season sample	Late July	1 day	Root colonization and soil chemistry at week 8
Late-season sample	Early Sept	1 day	Root colonization at week 12-14
Final harvest	Late Sept	1 week	Full root colonization, hyphal mapping, soil chemistry, plant biomass
Analysis	October	2-4 weeks	Staining, microscopy, data analysis, write-up

8.7 Success Criteria

Clear, binary decision criteria for each hypothesis:

- **H1 passes if:** Mean condensate yield exceeds 0.03 L/m2/night (all-nights average) over the monitoring period. Below this, the climate is unsuitable for radiative dew collection and the system should be trialed at a more humid site.
- **H2 passes if:** Mean mycorrhizal colonization at Group A lattice nodes is at least 2x colonization at Group A interstitial points (within-group spatial comparison), AND Group A node colonization exceeds Group C emitter-point colonization (between-group geometry comparison). Both comparisons must reach $p < 0.05$ by Mann-Whitney U test (non-parametric, appropriate for small samples).

> **What failure looks like:** H1 can fail if Fort Collins is too dry. This does not invalidate the system — it means the site is wrong. Trial at a more humid site. H2 can fail if geometry does not influence fungal colonization topology. This would mean the dripline is just irrigation, not a biome scaffold — still useful, but the novel claim is refuted. Both outcomes are clean and informative.

8.8 Cost and Materials

Minimum viable experiment (Groups A and C, 3 replicates each, 6 plots):

Item	Qty	Cost
Radiative panels (2 m2 foil + frame)	3	$60-90
HDPE drums (200 L)	3-6	$60-120
Drip tubing + jute + fittings	~30 m	$40-60
Mycorrhizal inoculant	1 bag	$15-30
Native plants (3 spp x 6 plots x 3/plot)	54 plants	$80-160
DHT22 temp/RH sensor + Arduino logger	1	$20-30
Soil moisture probes (capacitive)	6-10	$30-60
Trypan blue stain + slides + microscope time	1 kit	$30-50
Soil test kits (pH, Olsen P)	2 rounds	$40-60
Graduated cylinders / rain gauges	6	$20
Total (minimum, Groups A+C)		$395-660
Add Group B (tap water control)	+3 plots	+$100-150

This is a $400-650 experiment that tests a novel mechanism for directed biome construction. The radiative panel performance (H1) is a known-quantity replication. The geometry-driven colonization (H2) is the original contribution. If H2 succeeds, the result is publishable and the system has a defensible technical foundation. If it fails, you've spent less than a decent dinner out and learned something concrete.

Annotated References

Sources used to validate technical claims, organized by topic.

Radiative sky cooling (Sections 3, 4.1)

- **Beysens et al., "Application of passive radiative cooling for dew condensation," Energy, 2006** — Multi-site field study establishing yields and theoretical limits for passive dew collection. [ScienceDirect]
- **Khalil et al., "A review: dew water collection from radiative passive collectors," Sustainable Water Resources Management, 2016** — "A 1 m2 radiative condenser yields between 0.3 and 0.6 L/day in semi-arid regions." [Springer]
- **Maestre-Valero et al., "Comparative analysis of two polyethylene foil materials for dew harvesting," Journal of Hydrology, 2011** — Year-long field study in semi-arid Spain validating PE foil performance and 30-degree tilt geometry. [ScienceDirect]
- **Muselli et al. (2002), Atmospheric Research** — 30 m2 OPUR condenser in Corsica: 214 dewy nights over 478 days, average 0.12 mm/night per productive night. Key baseline for yield calculations. [Elsevier]
- **Zhao et al., "Radiative sky cooling: Fundamental principles, materials, and applications," Applied Physics Reviews, 2019** — Comprehensive physics review. Cooling power up to 140 W/m2. [AIP Publishing]
- **Zeyghami et al., "A review of clear sky radiative cooling," Solar Energy Materials and Solar Cells, 2018** — "A near-blackbody emitter achieves 6-8 degrees C below ambient." [ScienceDirect]

Ground-coupled air loop (Section 4.2)

- **Linacre, Airdrop Irrigation System (2011 James Dyson Award)** — Prototype producing ~1 L/day via underground condensation. [newatlas.com]
- **Wikipedia, "Ground-coupled heat exchanger"** — Confirms passive convective circulation possible and ground temp 10-23 degrees C at depth.

Desiccant sorption (Section 4.4)

- **MIT News, "Window-sized device taps the air for safe drinking water" (2025)** — Passive hydrogel-desiccant panel, no electricity needed. [news.mit.edu]

Thermoelectric harvesting (Section 5)

- **"Energy Harvesting from Natural Temperature Difference Between Soil Surface and Soil Depth," JSDEWES** — TEG module: max 27 mW from 3 degrees C differential. Validates power figures.

- **"Battery-Less Environment Sensor Using TEG from Soil-Ambient Air," PMC, 2022** — Validates self-powered sensing concept.
- **Analog Devices, LTC3108 datasheet** — "Input voltages as low as 20 mV." Confirmed operable from 1 degree C differential. [analog.com]

Mycorrhizal biome scaffolding (Section 6)

- **Requena et al., "Management of Indigenous Plant-Microbe Symbioses Aids Restoration of Desertified Ecosystems," Applied and Environmental Microbiology, 2001** — Long-term Mediterranean experiments: AM fungi + rhizobia inoculation enhanced plant establishment and increased soil fertility. [PMC]
- **Coban et al., "Soil microbiota as game-changers in restoration of degraded lands," Science, 2022** — Identifies mycorrhizal fungi, N-fixing bacteria, and PGPR as the most valuable groups for dryland restoration. [science.org]
- **Asmelash et al., "The Potential Role of Arbuscular Mycorrhizal Fungi in the Restoration of Degraded Lands," Frontiers in Microbiology, 2016** — AM inoculation promotes P-solubilizing rhizobacteria which act as mycorrhiza-helper-bacteria. Positive feedback cascade. [PMC]
- **Weemstra et al., "Review: roles of mycorrhizal symbioses in ecological restoration," Plant and Soil, 2024** — AM communities evolve with plant communities after revegetation; native inoculants outperform exotic. [PMC]
- **Zhang et al., "Impact of Irrigation Strategies on Tomato Root Distribution and Rhizosphere Processes," Frontiers in Plant Science, 2020** — SDI: 13.6% mycorrhizal colonization vs 10.8% for furrow irrigation. Higher microbial activity in SDI rhizosphere. [PMC]
- **Hao et al., "Influence of different irrigation methods on alfalfa rhizosphere soil fungal communities," PMC, 2022** — Drip irrigation shifts fungal communities; ectomycorrhizal and AM abundance affected by irrigation method. [PMC]
- **Burke and Scott, "Mycorrhizal Response to Experimental pH and P Manipulation," FEMS Microbiology Ecology, 2016** — "Elevating pH significantly increased AM fungal colonization and total fungal biomass." Soil pH is a primary driver. [Oxford Academic]
- **SPUN, "How to Encourage Healthy Mycorrhizal Networks," 2025** — "Conventional tillage can decrease AM fungal diversity by up to 40%." Organic matter and minimal disturbance are key. [spun.earth]
- **Simard et al., "Do mycorrhizal network benefits increase with soil moisture stress?" PMC, 2012** — MN potential increased seedling survival; facilitation increases with water stress. Water transfer via networks may play a role. [PMC]
- **Degradation of Biodegradable Nonwoven Mulches, PMC, 2024** — "Soil organic carbon content was higher under jute and hemp mulches." Jute enriches soil C at burial depth. [PMC]

Climate data

- **USDA, Fort Collins Soil Series** — "Mean annual soil temperature: 8-13 degrees C." [soilseries.sc.egov.usda.gov]

- **Weather-and-Climate.com, Fort Collins and Decatur** — Nighttime temps, humidity, sunshine hours. [weather-and-climate.com]
- **NWS Denver/Boulder** — Fort Collins station pressure ~840 hPa. [forecast.weather.gov]

End of document. This specification is released for open development and prototyping. Build, test, measure, iterate.