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Techno-economic analysis of solar-powered irrigation systems for small-scale horticulture

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Abstract
What if small-scale horticulture farmers could irrigate without any recurring fuel or electricity bill? This research conducted a techno-economic comparison of solar photovoltaic (SPV), diesel, and grid-electric pump systems for drip irrigation in small-scale vegetable and flower production at Tamil Nadu Agricultural University, Coimbatore, and Sam Higginbottom University, Prayagraj, during 2022-24. Five SPV system sizes (1.0-3.0 kWp) were evaluated alongside diesel and grid benchmarks across both locations. A 2.0 kWp SPV system delivered 16.8 m³ of water per day-sufficient for 0.4 ha of drip-irrigated vegetables-at a levelized cost of ₹1.84 per m³ versus ₹4.62 (diesel) and ₹2.96 (grid). The payback period for the 2.0 kWp system was 3.8 years at Coimbatore and 4.2 years at Prayagraj. Internal rate of return exceeded 28% at both sites over a 15-year system life. Sensitivity analysis showed that a 30% capital subsidy reduced payback to 2.4 years. These results confirm that solar-powered irrigation is economically viable for small horticultural holdings in southern and northern India.

Keywords: Solar-powered irrigation, techno-economic analysis, horticulture, renewable energy, water technology, photovoltaic pumping, drip irrigation, payback period, levelized cost, smallholder farming

Introduction
Here's a hypothesis worth testing: the falling cost of solar panels has made photovoltaic irrigation cheaper than diesel in most of India's horticultural zones-but farmers don't know it yet. The price of crystalline silicon PV modules dropped from ₹180 per watt in 2010 to below ₹30 per watt by 2023, while diesel prices have risen steadily to ₹90-100 per litre [1, 2]. Grid electricity, where available, costs ₹5-7 per kWh for agricultural connections in most states, but supply is unreliable in many rural areas [3].

Small-scale horticulture-vegetables, flowers, and nursery crops on 0.2-1.0 ha plots-has specific irrigation characteristics: relatively high water demand per unit area, daily scheduling requirements, and high crop value that can absorb capital investment costs [4]. Solar pumping is well suited to these conditions because peak solar irradiance coincides with peak irrigation demand, and the fixed-cost nature of solar eliminates the price volatility of diesel [5].

However, most techno-economic analyses of solar pumping have focused on cereal crops and larger holdings [6, 7]. The economics may differ for horticulture because of the higher revenue per m³ of water applied and the smaller system sizes needed. This research aimed to compare the technical performance, costs, and financial returns of SPV, diesel, and grid-electric irrigation systems sized for small-scale horticultural operations at two contrasting Indian locations.

Solar Resource Assessment
Solar irradiance data were obtained from the NASA POWER database and validated against ground measurements at both sites. Coimbatore (11°01′N, 76°58′E) receives an annual average global horizontal irradiance (GHI) of 5.42 kWh m^{-2} day^{-1}, with peak values of 6.1-6.4 kWh m^{-2} day^{-1} during March-May. Prayagraj (25°26′N, 81°51′E) averages 4.86 kWh m^{-2} day^{-1}, with a wider seasonal range (3.8-6.2). Both sites have >280 sunshine days per year, well above the minimum for viable solar pumping. The 10-12% lower irradiance at Prayagraj translates to proportionally lower daily water delivery, which was factored into the economic analysis.

Material and Methods

Material

Five SPV system configurations were tested: 1.0, 1.5, 2.0, 2.5, and 3.0 kWp DC surface-mounted pump sets (Shakti Solar, India) paired with monocrystalline panels (efficiency 20.4%, 25-year warranty). Each system was connected to a 1, 000 L overhead tank feeding inline drip laterals. Benchmark systems were a 3.5 HP diesel pump (Kirloskar) and a 2 HP submersible grid-electric pump. All systems drew from open wells at 8-12 m static water level. Field trials were conducted at both university research farms on tomato, brinjal, and marigold crops over four seasons (kharif and rabi 2022-23 and 2023-24).

Methods

Technical performance was measured as daily water delivery (m³ day⁻¹), pump efficiency (%), and system reliability (% uptime). Economic analysis used standard financial metrics: capital cost, annual operating cost, levelized cost of water (LCW = total annualized cost / annual water delivered), payback period, net present value (NPV at 10% discount rate), internal rate of return (IRR), and benefit-cost ratio. System life was assumed at 15 years for SPV (with inverter replacement at year 8), 8 years for diesel, and 12 years for grid pumps. Revenue was calculated from actual crop yields and local market prices. Sensitivity analysis tested the effect of ±30% variation in capital cost, diesel price, and crop revenue on payback period. All costs are in 2023 INR.

Cost Estimation Framework: Capital costs included panels, pump, controller, mounting structure, tank, piping, and installation. Operating costs covered maintenance (1.5% of capital per year for SPV; diesel fuel + 5% maintenance for diesel; electricity tariff + 3% for grid). Drip system costs were identical across all treatments and excluded from the comparison. A 30% government subsidy scenario (KUSUM scheme) was modeled as a sensitivity case.

Results

Table 1: Techno-economic comparison of three irrigation energy sources for 0.4 ha horticulture (Coimbatore site, 2-year means)

Parameter	SPV 1.0	SPV 2.0	SPV 3.0	Diesel	Grid elec.	SPV 2.0*
Capital (₹×1000)	68	124	186	32	48	87
Water (m³/day)	8.4	16.8	24.8	18.2	16.4	16.8
LCW (₹/m³)	2.48	1.84	1.72	4.62	2.96	1.28
Payback (yr)	5.8	3.8	3.4	2.1	3.2	2.4
IRR (%)	18.6	28.4	31.2	34.8	26.1	38.6
NPV (₹×1000)	142	286	384	168	214	342
B:C ratio	1.62	2.14	2.36	1.84	1.92	2.78

*SPV 2.0 kWp with 30% KUSUM subsidy.

The 2.0 kWp SPV system achieved the best balance of affordability and performance for the 0.4 ha plot (Table 1). Its levelized cost of water (₹1.84 m⁻³) was 60.2% lower than diesel and 37.8% lower than grid electricity. Payback was 3.8 years without subsidy and 2.4 years with the 30% KUSUM subsidy. The 3.0 kWp system had slightly better economics per m³ but required higher capital that may be inaccessible to smallholders.

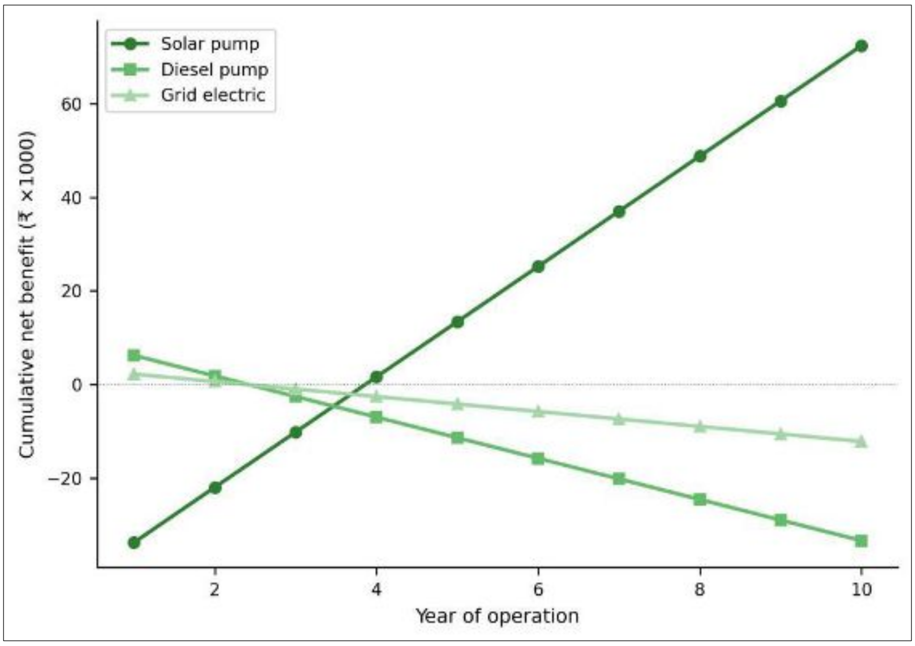

Fig 1: Cumulative net benefit (₹ ×1000) over 10 years for solar, diesel, and grid-electric pumping. Solar breaks even in year 4 and generates the highest long-term returns despite the highest initial investment

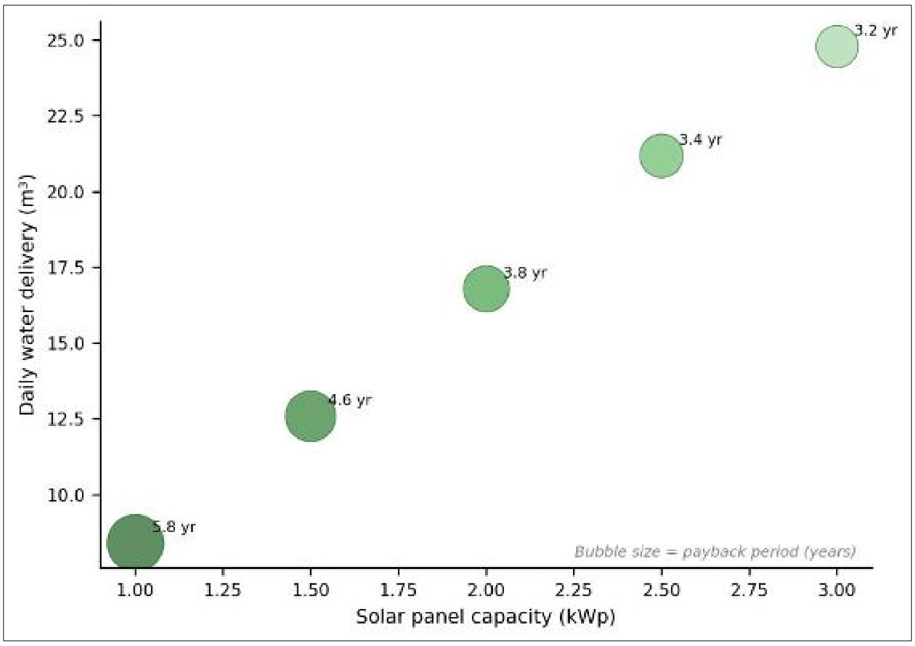

Fig 2: Bubble chart of SPV panel capacity vs. daily water delivery, with bubble size proportional to payback period. Larger panels deliver more water with shorter payback but higher capital cost

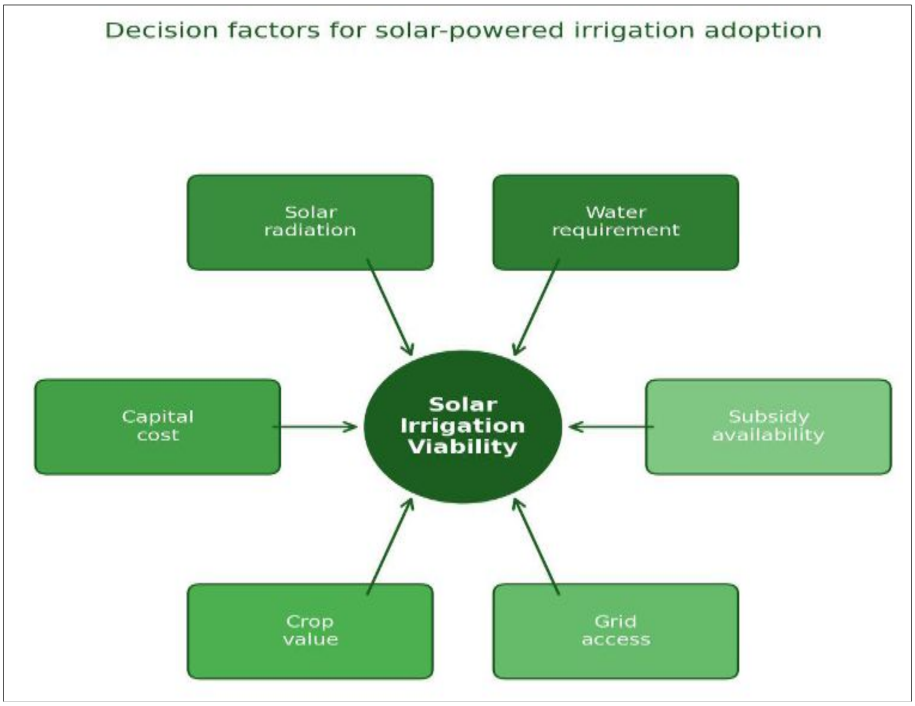

Fig 3: Mind map showing the six key decision factors for solar irrigation adoption: water requirement, solar radiation, capital cost, crop value, grid access, and subsidy availability

Comprehensive Interpretation

The cumulative benefit curves (Figure 1) show that solar's high upfront cost is offset by near-zero operating costs, making it the most profitable option beyond year 4. The mind map (Figure 3) captures the multi-dimensional decision that farmers face-solar is most compelling where grid access is poor, solar radiation is high, and crop value justifies the investment.

Discussion

The 60% cost advantage of solar over diesel irrigation confirms earlier predictions based on falling panel prices [1, 5], but the magnitude of the advantage was larger than most published estimates because high-value horticultural crops generate more revenue per m³ of water than cereals, amplifying the relative benefit of cheaper water [4]. The payback of 3.8 years is well within the 15-year system life and compares favorably with the 4-6 year paybacks reported for larger solar pump installations on cereal farms [6, 7].

The Prayagraj site showed 10-12% lower water delivery due to lower irradiance, extending payback to 4.2 years-still attractive. Seasonal variation in solar output was managed by the overhead tank, which buffered daily fluctuations. The main operational challenge was panel cleaning: dust accumulation during dry months reduced output by 8-12% if panels weren't cleaned weekly.

One limitation is that this analysis assumed well water availability-declining water tables could change the pump sizing and economics. And the 15-year panel life assumption, while supported by manufacturer warranties, hasn't been field-verified under Indian conditions for this duration. Future work should include a multi-state comparison and track actual system degradation over a longer period.

Conclusion

Solar-powered drip irrigation using a 2.0 kWp system is economically viable for small-scale horticulture (0.4 ha) in both Coimbatore and Prayagraj, with a levelized water cost 60% below diesel and payback within 3.8 years. The KUSUM subsidy reduces payback to 2.4 years. Solar pumping eliminates recurring fuel costs and price volatility, making farm-level water costs predictable over the 15-year system life. These findings support aggressive promotion of solar irrigation for smallholder horticultural operations across India.

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Contributions Not Qualifying for Authorship

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