Significant Boost in Energy Efficiency of High-Tech Greenhouse Bell Pepper Amid Projected Climate Scenarios

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Abstract

Global energy constraints demand a clearer understanding of how energy-efficient greenhouse food systems can adapt to future climate change. We analyse multi-year bell-pepper production in a high-tech glasshouse (Sydney, Australia) equipped with pad–fan evaporative cooling and hot-water heating, using 5-minute operational data captured by a Priva control system across four trials. Seasonal heating and cooling demands varied by more than an order of magnitude, driving large swings in energy intensity. Elastic-net regression (with bootstrapping) identified internal/external temperature (and their difference) and solar irradiance as the strongest, season-dependent predictors of energy use, highlighting opportunities for demand-side management (e.g., strategic pre-heating during off-peak tariffs).

We model five cropping windows to test seasonally adaptive strategies: skipping spring, summer, autumn, or winter, and year-round production. Skipping winter minimised energy input (3.92 $kWh \cdot kg^{-1}$), whereas year-round production maximised total output and economic potential (AUD 26.73 million) for a representative 50,000 m^2 facility with a dedicated nursery and packing shed. Labour plus energy comprised over half of annual operating costs, underscoring the dual mitigation and cost-control leverage of energy-efficient scheduling. To demonstrate applicability to Asian mega-cities, we benchmarked economic potential for a comparable facility in Shanghai, China.

Finally, by integrating trial-season regression with CMIP6/IPCC Shared Socioeconomic Pathways (2025-2050), we forecast a general decline in energy per unit yield driven by reduced winter heating demand. Collectively, these results show that seasonally adaptive cropping calendars and targeted energy strategies can enhance the sustainability, carbon efficiency, and resilience of pad–fan greenhouses in a warming climate, while supporting reliable urban fresh-produce supply.

Keywords: Bell pepper; Protected cropping; Resource use efficiency; Greenhouse seasonal planning; Climate change adaptation; Sustainable agriculture