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Review

Southeast Asia–Anchored Review of Pitahaya as Conditional Climate Adaptation in the Philippines

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Abstract: Pitahaya (*Hylocereus*/*Selenicereus* spp.) is expanding in the Philippines as a diversification option under increasing heat and rainfall variability, yet its environmental, economic, social and biosecurity implications remain fragmented. Methods: A structured narrative review of Web of Science and Scopus (2010-2025; English) was conducted using transparent title, abstract and full-text screening. Studies were classified by type and by transferability score (high, medium, conditional/low), summarised in evidence-transferability matrices. Results: Studies indicate red pitahaya grows best at 25–30 °C, 600–1300 mm annual rainfall, and under drip irrigation with mulches, but yields drop with waterlogging, heat above 35 °C, or salinity. In humid lowlands, disease (e.g. Neoscytalidium stem canker) often limits production, so clean planting material, ventilated trellising and canopy sanitation are important. Prices are shaped by Vietnam–China trade; in the Philippines, better postharvest practices and coordinated marketing can extend storage from 4 to 6 weeks and reduce rejections. As a non-native crop, pitahaya requires safeguards on planting material, nurseries, and site selection. Conclusions: With clean-plant governance, quality-first postharvest and producer coordination, pitahaya offers conditional, context-dependent climate adaptation. Targeted pilots and new Philippine data on life-cycle performance, employment, and biodiversity are priorities to guide responsible scale-up.

Keywords: pitahaya; climate adaptation; biosecurity; socio-economic impacts; agricultural diversification; Philippines

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1. Introduction

Climate variability and warming are reshaping tropical horticulture, intensifying heat and drought stress while altering pest and disease dynamics. Perennial fruit systems are especially exposed because their phenology and flowering cues are tightly linked to temperature and day length, and because orchard investments lock farmers into multi-year decisions (Trivellini et al., 2020; Sosa et al., 2020). In this context, climate-adaptive diversification with stress-tolerant species has become a central pathway for risk reduction in Southeast Asian (SEA) smallholder landscapes. Pitahaya—also known as dragon fruit—has emerged as a candidate diversification crop owing to its crassulacean acid metabolism (CAM), which confers high intrinsic water-use efficiency and the capacity to maintain photosynthesis under episodic heat and limited water (Sosa et al., 2020; Trivellini et al., 2020).

Pitahaya (*Hylocereus/Selenicereus spp*.) is a long-lived, trellised climbing cactus cultivated across tropical and subtropical regions. The CAM pathway (night-time CO_2 fixation) reduces transpirational losses relative to many C_3 fruit trees, making the crop attractive for dry seasons, marginal soils, and heat-prone areas (Trivellini et al., 2020). Beyond physiology, production can be scheduled more flexibly than many tree fruits: growers manipulate canopy vigour and photoperiod to induce off-season flowering, which supports premium pricing but also introduces energy footprints and management complexity (Xiong et al., 2020; Chien et al., 2024).

SEA has been a global hotspot of pitahaya intensification, with Vietnam's industry often cited for its widespread use of nighttime light supplementation to secure year-round flowering and fruiting (Nguyen et al., 2021a). Recent horticultural studies corroborate that photoperiodic lighting—together with net-houses to moderate microclimate—can raise fruit set and improve quality in red-fleshed cultivars, while emphasizing trade-offs in energy use and labour (Xiong et al., 2020; Chien et al., 2024). These agronomic levers are now diffusing to neighbouring countries, informing how growers in monsoonal climates buffer against irregular rainfall and temperature swings.

In the Philippines, pitahaya, an introduced climbing cactus, has transitioned from a novelty crop to a recognised diversification option over the past decade (Sharma et al., 2021). Peer-reviewed work from the Philippines documents both the crop's promise and emerging biological constraints. Two pathogens have drawn particular attention: stem necrotic brown spot caused by *Epicoccum sorghinum* and stem canker associated with *Neoscytalidium dimidiatum* (Taguiam et al., 2020a, Balendres et al., 2022).

Pollination biology adds another layer of context-specific risk. Many commercial clones of *Hylocereus undatus* are partially self-incompatible, and natural nocturnal pollinators (bats, hawkmoths) may be unreliable in cultivated landscapes; consequently, hand pollination or interplanting of compatible cultivars is widely used to stabilize fruit set and improve fruit size (Valiente-Banuet et al., 2007; Moreira et al., 2022; Wang et al., 2023). Although hand pollination can secure yields, it increases labour requirements and concentrates night work into narrow flowering windows—factors with equity and occupational-health implications for smallholders (Valiente-Banuet et al., 2007; Moreira et al., 2022).

Because pitahaya is non-native in the Philippines, ecological safeguards deserve explicit consideration. While robust, peer-reviewed Philippine data on naturalization are limited, international evidence indicates that *Hylocereus/Selenicereus* taxa can establish beyond cultivation under certain conditions; for example, ongoing control of *Hylocereus undatus* regrowth has been reported in protected areas in South Africa, and biosecurity assessments in other subtropical regions flag invasive potential where climbing supports and dispersal vectors are present (Foxcroft et al., 2023; Derviş et al., 2023). Translating these insights to SEA suggests that orchard placement near sensitive habitats, sanitation (removal of volunteers), and trellis-bound production should be integral to diversification programs.

This narrative review was undertaken to identify and synthesize the agronomic, environmental, and socio-economic factors that shape the viability and performance of *Hylocereus undatus* in the Philippines, contextualized by leading SEA producers (Vietnam, Thailand, Indonesia) and China's influence as the dominant external market, with reference to global evidence where relevant.

Partial objectives:

1. Identification of SEA pitahaya production systems and management levers (pollination, lighting, pruning, nutrition, and plant protection) and practice-ready options relevant to Philippine conditions.
2. Summarization of environmental outcomes (disease pressures, control effectiveness, water and energy use, biodiversity interactions) together with contextual drivers and mitigation approaches observed.
3. Determination of market and livelihood effects for smallholders and producers' groups, noting the key pitahaya market drivers for SEA supply chains.
4. Assessment of transferability to the Philippines setting, notably practices directly adoptable, those requiring adaptation and areas where evidence is insufficient (with recommendations).

Relative to existing global and Mediterranean pitahaya syntheses, this review makes three main contributions. First, it interprets agronomic, market and social evidence through a Southeast Asia–anchored lens, explicitly treating Vietnam, Thailand, and Indonesia as comparators for the Philippines rather than relying on extra-regional analogues. Second, it embeds pitahaya within a three-pillar climate-adaptation frame (environmental, economic, and social), so that trade-offs between water and energy use, disease pressure, price formation, and labour allocation are treated jointly rather than in separate literatures. Third, it introduces simple evidence-transferability matrices that combine study design, geography, and Philippine relevance to make the strength and portability of recommendations transparent.

2. Materials and Methods

A structured narrative review was undertaken to synthesize peer-reviewed evidence on Hylocereus undatus and close congeners (*Selenicereus* spp.) relevant to cultivation/management, postharvest/quality, economics/markets, social outcomes, and environmental impacts in the Philippines and transferable Southeast Asian (SEA) contexts.

Searches were conducted primarily in Web of Science and Scopus and limited to English-language journal articles published between 2010 and 2025. The 2010–2025 window was chosen a priori to capture the period of accelerated commercial expansion of pitahaya in SEA, contemporary cultivation and postharvest practices, and stabilized crop nomenclature following increased use of Selenicereus alongside Hylocereus. Earlier literature was considered less transferable to current production systems and markets.

The primary geographic emphasis was placed on Vietnam, Thailand, and Indonesia, identified as the most influential SEA producers/traders during 2010–2025. China was treated as a dominant external market and price/policy driver for SEA pitahaya; studies involving China–SEA trade, standards, or supply-chain dynamics were included when they directly shaped regional systems. The Philippines was prioritized as the target transfer context for relevance, while other SEA states were covered selectively where evidence was demonstrably transferable; given their minimal market share and influence, coverage was partial. Much of the quantitative supply-chain and community-level literature originates from Vietnam's export-oriented pitahaya sector, where institutional arrangements, market scale and border dynamics with China differ from those in the Philippines. We therefore treat Vietnamese findings as conditionally transferable: they inform hypotheses and illustrate potential trajectories but are not assumed to apply wholesale.

Harmonized crop names and taxonomic synonyms were applied (pitahaya, dragon fruit, pitaya, Hylocereus, Selenicereus). Search strings required at least one crop term and SEA geography term to appear in the title, abstract or keywords.

Table 1 Eligibility check structure for chosen literature

Eligibility check	Include (eligible if…)	Exclude (not eligible if…)
Topical relevance	Addresses cultivation/management, postharvest/quality, economics/markets, social outcomes, or environmental performance.	Pure food/biomedical chemistry without cultivation, postharvest, value-chain, or on-farm implications; taxonomic/genomic-only studies lacking cultivation/management relevance.
Geography / transferability	Conducted in SEA (with emphasis on Vietnam, Thailand, Indonesia, Philippines) OR presents clearly transferable findings to SEA conditions (comparable tropical agro-ecologies, smallholder structures, supply chains).	Conducted outside SEA without clear transferability to SEA/Philippine contexts (markedly different agro-ecology, markets, or policy settings).
Publication type/peer review	Peer-reviewed journal empirical or review articles.	Conference abstracts/notes, editorials, theses, preprints/non-peer-reviewed items.
Language	English.	Non-English.
Timeframe	Published 2010–2025.	Published outside the 2010–2025 window.

Chronological workflow follows given structure:

1. Screening titles/abstracts/keywords against eligibility criteria in Table 1.
2. Screening full texts for final inclusion.
3. Extracting key data into a table (study, country/region, environmental/economic/social signals, and relevance to the Philippines).
4. Narrative synthesis.

For each included study, additional descriptors were recorded: primary domain (environmental, economic, social), and an ordinal score for transferability to Philippine conditions (high/medium/conditional) and key finding of the included study. These descriptors underpin the evidence-based matrices in Sections 3.1–3.3 (Tables 2–4) and provide a modest quantitative backbone through simple counts by study type, domain, and transferability class. A formal meta-analysis was not attempted because outcome metrics, experimental designs, and context conditions were too heterogeneous for meaningful statistical pooling. Instead, effect directions and differences are emphasized where comparable.

3. Results and Discussion

3.1. Environmental performance

Environmental performance is assessed across four interacting dimensions: water and energy use; pest and disease pressures (and the plant-protection loads they drive); soil and nutrient dynamics; and biodiversity interactions, including naturalization risk.

3.1.1. Farming

As a CAM cactus, pitahaya fixes CO_2 predominantly at night and closes stomata by day, conferring high intrinsic water-use efficiency (WUE) relative to many C_3 fruit crops (Trivellini et al., 2020; Xu and Wang, 2024). Across sites, experimental and modelling work converge on an optimal thermal window for red-pitahaya around day/night 30/20 °C (corresponding to mean annual temperatures of roughly 25–30 °C), with productive orchards reported from lowland tropics receiving about 600–1300 mm annual rainfall and a pronounced dry season. Outside this window, resilience is conditional: established plants can withstand episodic drought and brief excursions above 38–40 °C, but repeated exposure to temperatures over 35 °C together with high irradiance increases the risk of sunburn, reduced net CO_2 uptake and higher disease susceptibility. Conversely, prolonged waterlogging and salinity depress growth despite CAM, especially on heavy or poorly drained soils. Shading and microclimate management can mitigate photoinhibition and heat damage in high-irradiance settings, while drip irrigation allows moderate deficit to be imposed without permanent stress (Trivellini et al., 2020; Hossain et al., 2021).

As a shallow-rooted cactus, pitahaya responds well to organic amendments and mulches, which stabilize moisture and support microbial activity (Trivellini et al., 2020). Multi-season nutrient trials indicate potassium is particularly important for fruit number and size, with cultivar- and site-specific optima (Fernandes et al., 2018). Over-supplying nitrogen can produce succulent tissues more susceptible to pathogen ingress, whereas balanced K and Ca support fruit firmness. Postharvest interventions such as calcium chloride dips can increase peel Ca, improve firmness, and suppress anthracnose lesion development, offering a relatively low-toxicity route to reduce waste (Awang et al., 2011).

3.1.2. Water use and irrigation

Reviews and orchard-level syntheses that include cactus/perennial systems consistently point to relatively low crop-coefficient (Kc) requirements for trellised pitahaya, while emphasizing that local calibration is essential because Kc varies with training system, fraction of ground cover and microclimate (Paredes et al., 2024). In practice, drip irrigation and surface mulching are repeatedly recommended: drip matches low but steady transpiration needs and reduces splash dispersal/wetness duration, while mulching lowers soil evaporation (Paredes et al., 2024; Mondol et al., 2025). Philippine Kc datasets remain sparse; however, regionally transferable evidence supports regulated-deficit or drip-based scheduling synchronized with pruning/lighting-induced flowering waves in monsoonal climates (Trivellini et al., 2020; Paredes et al., 2024).

3.1.3. Energy use and photoperiod manipulation

In Vietnam, Thailand and Taiwan, night-break lighting is widely used to induce off-season flowering/fruiting. Field experiments and grower studies show that supplemental lighting—and, in some cases, net-house enclosures—advance bloom, increase flowering waves, and improve winter/spring yields and fruit quality (Xiong et al., 2020; Chien et al., 2024). From an environmental standpoint, these gains trade off against electricity consumption and light-pollution externalities. Technology choice matters: compact fluorescents (CFL) and LEDs can achieve induction with markedly lower energy draw than legacy incandescent bulbs, pointing to substantial mitigation potential via fixture upgrades and tighter lighting windows (Nguyen et al., 2021a; Chien et al., 2024).

Artificial light at night (ALAN) has documented impacts on plant–pollinator networks: experiments show 62% reductions in nocturnal floral visits in illuminated plots and spillover effects on daytime interactions, sometimes reducing diurnal visitation depending on plant species (Knop et al., 2017; Giavi et al., 2021). While many pitahaya orchards rely on hand-pollination or interplanting compatible cultivars, the landscape-level biodiversity signal of large-scale night lighting is a legitimate concern near sensitive habitats. Practical mitigations include shielding, spectrum control, curfews and avoiding light spills toward adjacent natural vegetation.

3.1.4. Pathogens, inputs and losses

Environmental performance in humid monsoonal zones is strongly shaped by disease ecology. Across SEA (including the Philippines), stem canker associated with *Neoscytalidium dimidiatum* is now recognized as the most consequential pathology for pitahaya, reducing yield/quality and shortening orchard lifespan (Derviş et al., 2023; Taguiam et al., 2020a). Philippine studies also report necrotic brown spots caused by *Epicoccum sorghinum* on cladodes (Taguiam et al., 2020b). These pathogens flourish in wet, wound-prone canopies and can be introduced via contaminated nursery stock; hence, clean planting material, airflow-oriented trellising, sanitation (tool disinfection; removal of infected cladodes) and prudent fungicide rotation are central to reducing both chemical loads and losses (Derviş et al., 2023; Taguiam et al., 2020a, 2020b). EFSA's 2023 pest categorization adds weight by classing *Neoscytalidium dimidiatum* as a potential quarantine pathogen with broad climatic suitability, underscoring the biosecurity stakes for regional trade (Bragard et al., 2023).

3.1.5. Biodiversity interactions and naturalization risk

Because pitahaya is non-native in the SEA, escape from cultivation is a legitimate concern near forests or karst/limestone outcrops that provide climbing supports. In South Africa's Kruger National Park, for example, *Hylocereus undatus* appears in alien plant lists and requires ongoing control—an instructive analogue for invasion screening (Foxcroft et al., 2023). Translating this risk to SEA, regional floras already show high naturalized richness of American taxa, and invasion pressure is non-trivial in the Malaysian archipelago (which includes much of SEA); standardized compilations report substantial naturalized floras and ongoing homogenization of island floras due to alien plants (Holmes et al., 2023). Together, these strands support a precautionary stance: treat pitahaya as a potential garden-escape with the capacity to persist if propagules reach suitable supports and microclimates.

3.1.6. Evidence-based matrix

Overall, pitahaya's environmental performance depends on context. In dry or seasonally arid areas—and on shallow, degraded soils—its CAM physiology plus drip irrigation and mulching can keep water use low without relying on energy-intensive lighting. In humid lowlands and during the wet season, diseases drive outcomes: without clean planting material, good sanitation, and airy trellis designs, growers tend to use more fungicides and still lose yield. Off-season lighting can boost prices but adds energy use and light-pollution (ALAN) impacts; LEDs, shielding, and strict schedules help but don't remove these costs. Philippine invasion data are limited, but evidence elsewhere supports cautious siting and regular monitoring. With policies that combine diversification incentives with biosecurity (clean stock, nursery accreditation), integrated pest management, careful lighting, and circular resource use, pitahaya can be a low-water, climate-tolerant option.

Table 2 Evidence-based matrix – environmental performance

Study (author and year)	Country/Region	Environmental lever	Key finding	Relevance to PH?
Trivellini et al. (2020)	Mediterranean (transferable to tropics)	CAM physiology and drought/heat tolerance	Pitahaya (CAM) shows high intrinsic WUE; needs shading/microclimate under extreme heat.	High (dry/heat-stressed zones)
Paredes et al. (2024)	Global review	Orchard crop coefficients (Kc) and irrigation	Trellised cactus/dragon-fruit systems require calibrated FAO56 Kc; drip + mulches recommended.	High

Chien et al. (2024)	Taiwan (SEA-relevant)	Net-houses + off-season induction (non-energy details omitted here)	Net-house microclimate improves fruit set/quality; supports premium windows.	Conditional (capital, climate)
Xiong et al. (2020)	China (transferable)	Light-induced flowering pathways	Transcriptomics: CONSTANS/FT and hormones mediate induction; informs precise scheduling.	Medium
Knop et al. (2017)	Switzerland (ecology, transferable)	Artificial light at night (ALAN) impacts	ALAN reduces nocturnal floral visits; implies need for shielding/curfews near habitats.	Medium–High (biodiversity-sensitive areas)
Giavi et al. (2021)	Switzerland (ecology, transferable)	ALAN effects on diurnal networks	ALAN alters daytime pollination networks; manages light spill.	Medium–High
Derviş et al. (2023)	Global/SEA	Disease ecology—Neoscytalidium stem canker	Aggressive canker: clean stock, sanitation, airflow, and fungicide rotation needed.	High
Taguiam et al. (2020a)	Philippines	Neoscytalidium stem canker (susceptibility)	Confirmed canker; cultivar susceptibility profile for PH germplasm.	High
Taguiam et al. (2020b)	Philippines	*Epicoccum sorghinum* necrotic brown spot	Emerging cladode disease in humid conditions; hygiene and wound prevention are critical.	High
Bragard et al. (2023)	EU (risk assessment)	Pest/pathogen categorisation—*N. dimidiatum*	Potential quarantine pathogen with broad climatic suitability.	High
Foxcroft et al. (2023)	South Africa (transferable)	Naturalization risk in protected areas	H. undatus requires ongoing control post-removal; stresses containment protocols.	Medium–High

3.2. Economics and markets

In this section, synthesis of three tightly linked domains is done, that shape pitahaya profitability in the Philippines and SEA context: regional market structure and price formation (with Vietnam–China dynamics as key anchors), postharvest physiology and shelf-life management as direct levers for loss reduction and net revenue and consumer preferences and grading standards, which determine price tiers and rejection risk.

3.2.1 Regional market structure and price formation

Vietnam remains the regional reference point for pitahaya (dragon fruit) supply and pricing, historically exporting large volumes to China. Planning/harvest timing and distribution decisions on Vietnamese farms are strongly shaped by export windows and price uncertainty (Nguyen et al., 2019; Nguyen, 2024). Recent market/context studies also document the rapid expansion of China's own production (overtaking Vietnam by 2021) and the heavy reliance on nighttime lighting in major producing areas, which changes cost structures and seasonal availability (Zhan et al., 2025). These dynamics imply that Philippine growers primarily serve domestic demand at present, but their margins will still be influenced by regional price swings led by the Vietnam–China trade.

3.2.2. Postharvest physiology, shelf-life management and revenue

Net revenue in fresh chains is highly sensitive to losses from respiration, water loss, and decay. Recent pitahaya studies quantify respiration kinetics across temperature and O_2/CO_2, providing parameters for modified/controlled-atmosphere designs and cold-chain set points (Ho et al., 2020; Ho et al., 2021). Storage trials also show that combining low temperature with simple packaging can extend marketable life: for example, work on *Hylocereus undatus* found that 5–7 °C with appropriately ventilated plastic reduced shrivel and maintained quality (Freitas and Mitcham, 2013). Philippine trials with red-fleshed fruit harvested 25–30 days after flowering showed that modified-atmosphere packaging (PE or PP bags plus polystyrene fruit cups) combined with storage at 5 °C extended marketable life from about 4 weeks (non-packaged controls) to 6 weeks, with fruit remaining firm and bracts still green at removal. After cold storage, shelf life at 20 °C increased from roughly 2 days (non-MAP) to 3–5 days (MAP-packed fruit), directly reducing shrink and enabling longer domestic or inter-island shipments (Franco et al., 2022). A recent synthesis consolidates these advances and other preservation tools for pitahaya (Wang et al., 2024b). Where market access requires phytosanitary irradiation, contemporary reviews indicate that it can be compatible with fruit quality when paired with good cold-chain practice. Commodity-specific validation is still advised (Hallman, 2016; Golding et al., 2024). Together, these results justify investments in basic pre-cooling/cold rooms, liners, or MAP where appropriate, and pack-house QA—often yielding larger margin gains than expanding area.

3.2.3. Consumer preferences: what sells

Filipino buyers consistently pay for medium-size, clean/blemish-free peel, and fresh, green bracts, alongside sweetness and (for some segments) red flesh; credence attributes (price fairness, organic claims, declared origin) also matter (Gerance et al., 2020). Maturity at harvest and uniformity affect storability and sensory scores, reinforcing the value of standardized grading and maturity indices (Franco et al., 2022). These findings align with the postharvest evidence above: more disciplined picking and pack-out can cut rejections and raise average price without increasing planted area. Deterministic and stochastic optimization models calibrated for Vietnamese dragon-fruit chains show that multi-period harvest scheduling, forward-buying contracts, and coordinated distribution reduce waste and revenue volatility (Nguyen et al., 2019; Nguyen et al., 2021b; Nguyen et al., 2024). Although built on Vietnam data, the managerial levers are transferable: Philippine producer groups can synchronize pruning/flowering waves (with or without lighting), pre-commit volumes to buyers, and add simple pre-cooling at hubs to stabilize cash flow. On the product side, demand for processed/ready-to-drink formats is emerging; process studies show that consumer acceptance of dragon-fruit beverages depends on soluble solids, colour, and process parameters—opening channels for grade-out fruit and reducing waste (Pham et al., 2024). These diversification paths help hedge fresh-market volatility, provided food safety and branding are in place.

3.2.4. Energy use of night lighting, costs, and smallholder feasibility

Off-season “night-break” lighting is now widespread in SEA pitahaya, historically using incandescent bulbs but increasingly CFL/LED as growers switch to lower-energy options. Peer-reviewed studies and reviews consistently note the heavy electricity burden of incandescent systems and the shift toward efficient lamps to cut costs and emissions (Nguyen et al., 2021a; Wang et al., 2024a).

Typical trellised orchards carry roughly 1,100–1,300 posts (lights) per ha; some technical guidance and commercial deployments cite 1,000–2,000 lamps ha^{-1} depending on spacing and season

(Then, 2017; Rashid et al., 2021). With a common 4-hour night-break per night (1,200 lamps*0.1 kW*4 h) energy is:

- Incandescent 100 W: 480 kWh ha^{-1} $night^{-1}$
- CFL 26 W: 125 kWh ha^{-1} $night^{-1}$
- LED 9 W: 43 kWh ha^{-1} $night^{-1}$

These ratios (incandescent/CFL/LED) imply significant energy savings per lighting night when switching to efficient lamps. Farmer survey and field trials in Vietnam show off-season flowering commonly induced with 75–100 W incandescent lamps for 4–10 h per night; prototype 20 W CFL systems achieved comparable flowering, implying reductions in electricity use and operating costs for smallholders (Nguyen et al., 2021a). Exact numbers are available only in a non-peer-reviewed United Nations Environment Programme (2016) report from Vietnam, documenting large per-session electricity bill reductions after replacing incandescent bulbs with efficient bulbs (US$660–700 down to US$177–220 per lighting period on a family farm) which is consistent with the calculation above.

3.2.5. Evidence-based matrix – economics and markets

Regional price signals remain anchored in Vietnam's export-oriented chains and their exposure to China, with recent evidence that China's own output has expanded rapidly, shaping seasonal availability and margins across SEA. For the Philippines, this implies a primarily domestic strategy while staying sensitive to Vietnam–China swings. The clearest, near-term margin lever is postharvest discipline: respiration modelling and storage trials converge on low temperature plus appropriate packaging/MAP to slow loss, Philippine tests confirm fewer rejections and longer marketing windows, while reviews consolidate CA/MAP and coating options, phytosanitary irradiation can be compatible with quality when paired with a sound cold chain. At the market interface, Filipino buyers reward clean, medium fruit with fresh bracts and sweetness, so grading and maturity indices pay quickly. Coordination tools (multi-period scheduling, forward contracts, pre-cooling hubs) reduce waste and revenue volatility. Given domestic-market orientation and exposure to Vietnam–China price swings, Philippine producer groups can improve resilience by adopting CFL/LED night-break only when off-season premiums cover energy + labour and sharing capex (co-op bulk buys; standardized layouts of 1,000–1,300 lamps ha^{-1}). Where tariffs are high or service is unreliable, CFL/LED still reduces kWh by orders of magnitude versus incandescent, making the practice more economically and socially acceptable for smallholders (lower bills, fewer payment shocks).

Table 3 Evidence-based matrix – economics and markets

Study (author and year)	Country/Region	Economic lever	Key finding	Transferable to PH?
Nguyen (2019)	Vietnam	Harvest scheduling and contracts	Optimization shows that coordination reduces rejections and revenue volatility.	Conditional
Nguyen (2024)	Vietnam	Stochastic planning under uncertainty	Margins sensitive to price swings and rejection rates need robust planning.	Conditional

Chien et al. (2024)	Taiwan	Microclimate control (net-houses)	Improved fruit quality and timing can capture premiums.	Conditional
Nguyen et al. (2021)	Vietnam	Efficient induction fixtures	20 W CFLs achieved induction comparable to 60–100 W bulbs with lower power cost.	Yes
Ho et al. (2020; 2021)	Malaysia/Singapore	Respiration modelling → CA/MAP	Parameters guide MAP/CA design to extend shelf-life and reduce rejections.	Yes
Franco et al., (2022)	Philippines	MAP + cold storage	Red-fleshed pitaya retains its quality longer; supports inter-island logistics.	Yes
Gerance et al. (2020)	Philippines (urban buyers)	Grading to match preferences	Medium size, clean peel, fresh bracts, sweetness drives purchase and price.	Yes
(b)Wang et al. (2024)	Global review	Postharvest preservation options	Synthesizes storage/coating; informs pack-house investments.	Yes
Zhan et al. (2025)	China (regional signal)	Remote-sensed production structure	Night-time light intensity mirrors production scale: China overtook Vietnam by 2021.	Context only
Pham et al. (2024)	Vietnam (products)	Beverage/processing demand	Consumer acceptance depends on soluble solids and colour; supports processing hedges.	Conditional

3.3. Social outcomes

3.3.1. Livelihoods and household income

Across SEA, pitahaya has been used by smallholders as a risk-spreading cash crop with relatively quick bearing, modular expansion (row-by-row trellis), and strong urban demand. Mixed-methods work in Bình Thuận, Vietnam, combining satellite data with village interviews, documents how pitahaya adoption reorganized local farming calendars and household routines, expanded local service work (nursery stock, trellis fabrication, packing, trucking), and tied growers more closely to peri-urban and cross-border markets (Krauser et al., 2021). Philippine studies on consumer preferences and postharvest handling indirectly speak to incomes. A survey of 200 urban consumers found that more than 60% give highest weight to intrinsic attributes, freshness, peel colour, overall peel quality, and taste, when buying dragon fruit, and around two-thirds reported at least one purchase disappointment, mainly fruit that was not sweet enough or already deteriorating (Gerance et al., 2020). Households that can meet preferred traits (medium size, clean peel, fresh green bracts, sweetness) and maintain quality during transport therefore systematically access better price tiers and face fewer rejections. Put simply, upgrading basic harvest and pack-out practices (grading, liners/MAP, cool storage) is a household-level income lever as important as area expansion.

3.3.2. Employment and labour allocation

Published sources do not provide reliable headcounts of pitahaya-related jobs in the Philippines or wider SEA, so totals are not reported in this review. What the literature does show is a reallocation of household labour toward narrow reproductive windows: anthesis and effective pollination typically occur late evening to early morning, concentrating work into short, time-critical bouts often met by family labour or short-term hires (Tran et al., 2015; Cho et al., 2021). Where local ecology allows, integrating stingless bees has been shown to secure fruit set in red-fleshed pitahaya and reduce manual pollination workloads, smoothing these nocturnal peaks. That provides opportunities for smallholders who can adopt meliponiculture (Ador et al., 2024).

Beyond field tasks, the chain generates off-field roles in on-farm and village pack-lines (sorting, grading, quality checks, basic documentation), which studies of Vietnam's dragon-fruit supply chains highlight as regularized activities suggested to standard operating procedures. (Nguyen, 2019; Nguyen, 2024).

3.3.3. Local community effects

Beyond farm income, pitahaya clusters tend to stimulate supporting community services such as nursery propagation, trellis/post fabrication, packing, trucking, and basic cold handling. It is documented at community scale in Bình Thuận, Vietnam, where crop adoption reshaped daily routines and local enterprise activities (Krauser et al., 2021). In the Philippines, low-cost handling upgrades—notably modified-atmosphere packaging (MAP) with cool storage—extend marketable life and cut shrink for red-fleshed fruit, which stabilizes cash flow for small producers supplying distant towns and inter-island routes; these pack-out skills are readily transferable to co-op or barangay-level hubs (Franco et al., 2022). Parallel community opportunities emerge from pollination and by-products: in Malaysia (Sabah), field trials show stingless-bee pollination can deliver acceptable fruit set/quality in pitahaya, creating scope for meliponiculture micro-enterprises that reduce manual pollination needs while adding honey/by-product income (Ador et al., 2024). Waste streams can also be valorised locally: recent reviews and experiments identify pitahaya peel as a source of pigments, flours and bioactives with food, cosmetic and biomaterials applications (betalain extraction, microencapsulation, peel flours) (Jiménez-García et al., 2022; Otálora et al., 2023; Taharuddin et al., 2023; Coelho et al., 2024). Finally, tropical fruit-peel recycling into feed ingredients is gaining evidence, suggesting community-level links between fruit hubs and nearby livestock keepers (Wanapat et al., 2024). Together, these studies point to community-positive effects when smallholders can access training, light-asset credit (crates, liners, simple cool rooms), pollination services, and reliable local buyers, while by-product use offers additional pathways for village-scale enterprises.

3.3.4. Training and certification towards stability

Evidence from peer-reviewed studies shows that the social "enablers" around pitahaya—farmer training with buyers, certification/standards, and labour-saving pollination options—shape who participates and how stable household incomes are.

A policy article on Vietnam's pitahaya sector documents how GAP-based quality systems, driven by Ministry of Agriculture and Rural Development and implemented through exporter/packer–farmer group pilots, manuals, and joint trainings, expanded certification and formalized producer groups (30–100 households), strengthening traceability, process control, and links to higher-value markets. By 2017, about 10,083.5 ha had GlobalGAP/VietGAP certification, illustrating how institutional support and buyer-linked training can broaden smallholder participation and stabilize quality (elements that are readily adaptable to Philippine co-ops targeting supermarket/export channels) (Uyen et al., 2018).

On standards, quasi-experimental evidence from Vietnam's fruit sector shows VietGAP adoption increased revenue and profit (while modestly raising labour costs) among smallholders; this points to a trade-off—higher income and market access in exchange for more disciplined practices and record-keeping. Although the study is on longan (*Dimocarpus longan*), the mechanism (training + process control + traceability) is directly transferable to pitahaya producer groups seeking supermarket/export channels (Thanh Truc and Thuc, 2022).

3.3.5. Certification and agritourism in community context

Fruit-cantered place-branding can translate orchards into visitor experiences that diversify smallholder income and stimulate community services (guiding, food stalls, transport). In the Philippines, Guimaras' mango-driven rural development shows how a flagship fruit underpins tourism, identity, and local enterprise, while also revealing vulnerability to climate shocks that jeopardize festival seasons and farm visits, providing opportunity for pitahaya clusters to consider agritourism as a supplement to main crop – mango (Hrušovský et al., 2024).

Peer-reviewed evidence from Viet Nam indicates that agritourism's social payoff depends on institutional design. A study of public–private partnerships (PPPs) in the Mekong Delta finds that when destination development is coordinated with farmer groups and buyers, communities gain skills, market links, and shared infrastructure—conditions directly applicable to pitahaya hubs seeking to host farm tours, tasting and short courses (Nguyen Hoang Thanh and Lee, 2025).

Agritourism around pitahaya can strengthen the social pillar by stabilizing household cash-flow through small, frequent service revenues, catalysing community micro-enterprises (food stalls, crafts, transportation). To prevent inequity and participant fatigue, programs should institutionalize fair participation and rotation of host farms, ensure basic training and transparent pricing, and maintain contingency plans for climate-affected seasons.

3.3.6. Evidence based matrix – social outcomes

Overall, pitahaya can enhance household resilience through quick-bearing, modular plantings and quality-driven price gains when basic pack-out and cold handling are in place. Labor is reallocated toward narrow reproductive windows, but managed pollination (e.g., stingless bees) and standardized pack-house routines can temper nightwork and broaden roles—often benefiting women and youth in sorting, grading, and QA. At community scale, clusters catalyse support services (nurseries, trellis fabrication, packing, transport) and open by-product micro-enterprise options (peel pigments/flours, feed links).

Table 4 Evidence based matrix – social outcomes

Study (year)	Country/Region	Social lever	Key finding	Transferable to PH?
Krauser et al. (2021)	Vietnam (Bình Thuận)	Community restructuring; ancillary services (nursery, trellis, packing, transport)	Village-scale evidence of service growth; tighter market linkages	Conditional
Gerance et al. (2020)	Philippines (urban buyers)	Price premiums for cosmetic/sensory quality	Medium size, clean peel, fresh bracts valued by consumers	Yes
Franco et al. (2022)	Philippines	MAP + low-temperature storage reduces shrink	Extends marketing window; supports inter-island shipping	Yes
Nguyen (2019)	Vietnam	Scheduling, forward contracts, coordinated logistics	Models show benefits of coordinated harvest and contracting	Yes
Nguyen (2024)	Vietnam	Stochastic supply-chain planning under uncertainty	Margins sensitive to price and rejection volatility	Conditional
Tran et al. (2015)	Vietnam	Pollination method × fruit set (labour timing)	Tight windows shape labour peaks (evening/morning)	Yes
Cho et al. (2021)	Korea (transferable biology)	Floral biology and hand-pollination need	Confirms narrow anthesis window	Conditional
Ador et al. (2024)	Malaysia (Sabah)	Stingless-bee pollination as labour-saving service	Meliponiculture can reduce manual pollination workloads	Conditional
Hrušovský et al. (2024)	Philippines	Sustainable development through agritourism	Pitahaya as a complementary crop to mango branded Guimaras island and an off-season agritourism draw	Yes
Derviş et al. (2023)	Global/SEA	Disease shocks (canker): household risk	Biosecurity and sanitation critical to avoid disruptions	Yes
Jiménez-García et al. (2022)	Global review	By-product valorisation (peel phytochemicals)	Peel as source of pigments/flours/bioactives for small processing	Conditional

3.4 Conceptual framework

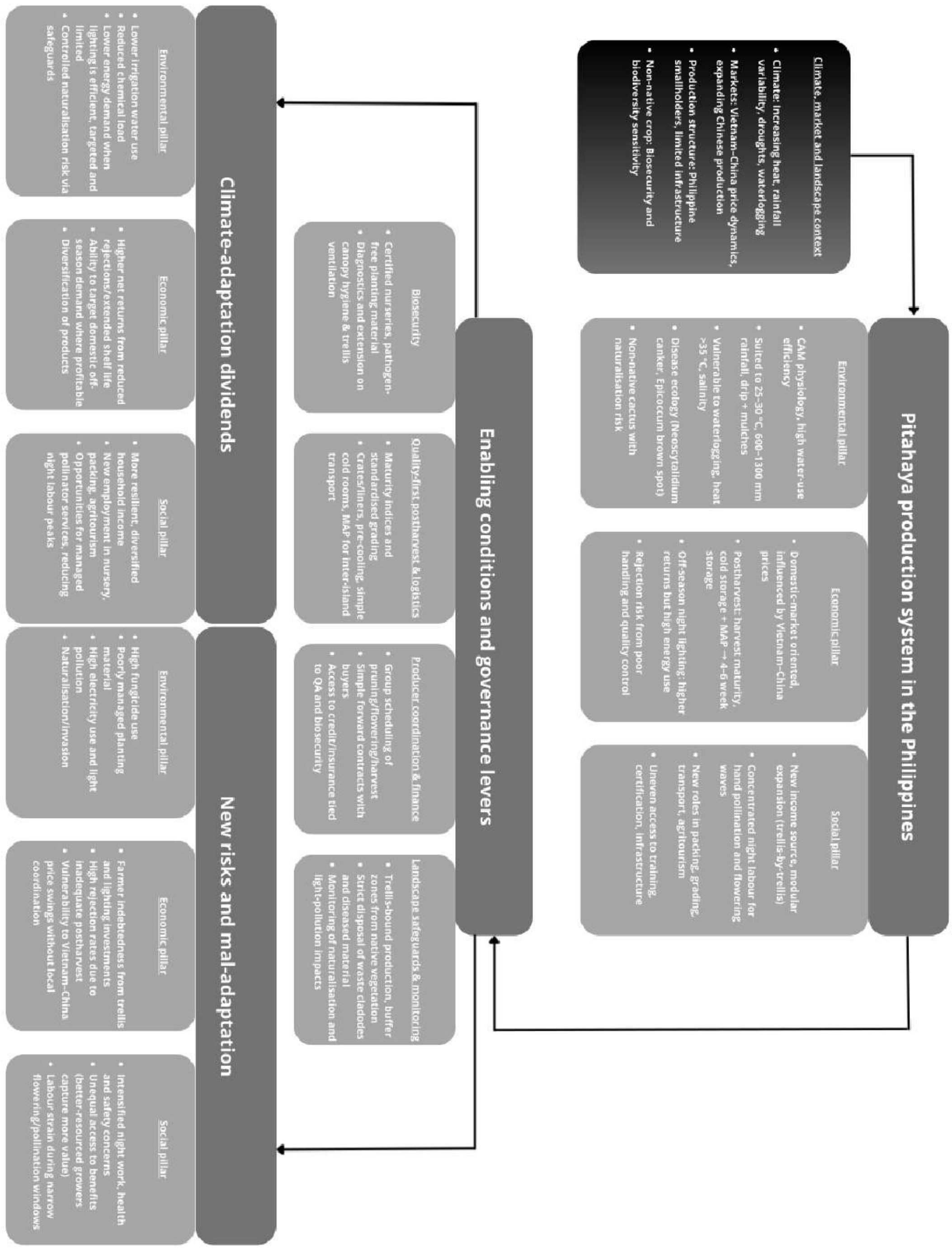

Figure 1. Conceptual framework of pitahaya as a conditional climate-adaptation option for Philippine smallholders

Climate variability, market dynamics and the crop's non-native status shape the context in which pitahaya is adopted. Within Philippine smallholder systems, pitahaya interacts with environmental (water use, disease ecology, biodiversity), economic (postharvest quality, markets, energy use) and social (labor allocation, livelihoods, community services) dimensions. Governance and management "enablers", clean-plant systems, quality-first postharvest and logistics, producer coordination and finance, and landscape safeguards, determine whether pitahaya delivers climate-adaptation dividends (reduced water stress, more stable incomes, diversified livelihoods) or instead generates new environmental, economic, and social risks (disease-driven chemical use, energy-intensive lighting, naturalization, income volatility). The framework emphasizes that pitahaya's adaptation role in the Philippines is conditional and context-dependent rather than automatic.

4. Discussion

Recent pitahaya reviews emphasize plant biology/agronomy or postharvest, often from Mediterranean or global vantage points. For example, Trivellini et al. (2020) synthesize CAM physiology, low water use, and protected-culture practices to argue pitahaya's promise for water-limited regions; this review's environmental synthesis corroborates the water-thrift claim, but stresses humidity-driven disease risks and context-dependent heat limits in tropical monsoons—framing "low water" as a conditional advantage rather than a blanket one.

On postharvest, Wang et al. (2024b) provide a broad technical review of respiration, storage temperatures, coatings, and quality decline. The agreement can be found on the centrality of cold/MAP and add Philippines-specific evidence (MAP + cool storage field trials) to show how small, distributed pack-house upgrades translate into household-level margin gains and longer marketing windows—making the economics explicit rather than purely physiological.

Reviews in genetics/biotechnology (Tel-Zur, 2022; Shah et al., 2023; Xu and Wang, 2024) map self-incompatibility, flowering genetics, and breeding pipelines. Our synthesis takes these biological insights but re-anchors them in policy and management choices relevant to the Philippines/SEA (clean-plant systems, nursery accreditation, cultivar choice to reduce hand-pollination). In short, where biotech reviews emphasize *"what is biologically possible"*, this review emphasize *"what reduces environmental, economic and social costs."*

Finally, the broader pitahaya literature (Tarte et al., 2023; Chen et al., 2024) is rich on nutritional/health and processing/value-addition potential (pigments, beverages), but these papers rarely integrate market coordination or household-level implications. The gap is plugged by pairing postharvest controls with consumer preference data (Philippines) and supply-chain optimization evidence (Vietnam) to show where smallholders capture value: quality-driven price tiers, lower rejections, and coordinated harvest scheduling (Nguyen et al., 2019; Gerance et al., 2020).

In addition to qualitative synthesis, the review introduces modest quantification of key trade-offs using published data. Simple per-hectare calculations for night-break lighting show that shifting from 100 W incandescent bulbs to 26 W compact fluorescents or 9 W LEDs can reduce electricity demand per lighting night by roughly three- to ten-fold, with corresponding cuts in costs and emissions (Then, 2017; Nguyen et al., 2021a; Rashid et al., 2021). Philippine trials combining modified-atmosphere packaging with cold storage likewise demonstrate that low temperature and simple packaging can extend marketable life of red-fleshed pitahaya relative to non-packaged controls and lengthen post-storage shelf life at ambient temperature, translating into fewer rejections and more stable revenue (Freitas and Mitcham, 2013; Franco et al., 2022). These order-of-magnitude comparisons provide a quantitative backbone to the narrative discussion of environmental and economic trade-offs.

This review's main strength is its Southeast Asia–anchored perspective: interpretation of agronomy, markets, and social dynamics through cross-checking SEA experiences, which keeps recommendations for the Philippines conditions realistic rather than imported from non-tropical contexts. A second strength is the three-pillar integration—environmental, economic, and social—so disease ecology, postharvest quality/market access, and household labor are treated together, yielding concrete, policy-ready levers. Finally, the structured evidence matrices make coverage and transferability explicit, helping readers see where findings are robust versus tentative.

The chief limitations arise from context imbalance and evidence gaps. Much of the quantitative supply-chain and community evidence is Vietnam-heavy, whereas Philippine microdata (employment counts, household panels, province-level time series) remains sparse. Key externalities are also under-documented: there are, yet, no Philippine life-cycle assessments benchmarking pitahaya against mango or pineapple, and few landscape-scale biodiversity studies around trellis-bound orchards; invasion risk is inferred from analogues rather than domestic monitoring. Finally, markets and pathogens are evolving quickly, so any synthesis bounded to 2010–2025 risks being outpaced by new price dynamics or disease pressures.

These gaps suggest a forward-looking research agenda with three clusters. First, Philippine-specific biophysical work is needed on irrigation crop coefficients, life-cycle assessments that compare pitahaya with incumbent fruit crops, and biodiversity/naturalization monitoring around orchards in different landscapes. Second, socio-economic and labor studies should document employment headcounts, income volatility, and gendered labor allocation under different pollination (manual versus managed pollinators) and postharvest (basic versus upgraded cold chain) scenarios. Third, policy and pilot evaluations are required to test alternative arrangements for clean-plant systems, nursery accreditation, producer coordination, and agritourism/public–private partnerships. Designing diversification programs as monitored pilots within these domains would allow pitahaya's "conditional adaptation" role to be empirically tested rather than assumed.

Finally, markets and pathogens are evolving quickly, so any synthesis bounded to 2010–2025 risks being outpaced by new price dynamics or disease pressures, so periodic updates will be needed as fresh Philippine data and regional assessments emerge.

5. Conclusions

Pitahaya can be a useful but conditional diversification crop for Philippine smallholders. Its CAM physiology and trellised, modular production suit water-limited or degraded sites, and domestic demand rewards quality when harvest maturity, grading, and basic cold handling are in place. However, outcomes hinge on context and governance: in humid lowlands, disease ecology (especially Neoscytalidium stem canker) can drive chemical use and losses without clean planting material, airflow-oriented trellising, and sanitation. Because pitahaya is a non-native cactus with naturalization potential, landscape safeguards (trellis-bound production, buffers from native vegetation, strict waste-cladode handling) are prudent to manage biodiversity risks.

Economically, the most reliable near-term gains come from quality-first value chains—maturity indices, standardized grading, crates/liners, pre-cooling/modified-atmosphere packaging—and from producer coordination (synchronized pruning/harvest waves, basic contracts with buyers) that reduces rejections and revenue volatility. Socially, pitahaya reshapes household labor around narrow reproductive windows but also creates off-field roles in sorting, grading, agritourism and documentation; where feasible, managed pollinators such as stingless bees can ease manual pollination loads and broaden participation. Policy priorities are clear:

1. clean-plant backbone (nursery accreditation, diagnostics, extension on canopy hygiene)
2. postharvest basics at barangay/co-op hubs (simple cold rooms, SOPs for grading/MAP)
3. coordination and finance tools (group scheduling, forward agreements, micro-credit/insurance tied to QA/biosecurity)
4. landscape safeguards to minimize environmental externalities.

Given the Vietnam-heavy nature of the current evidence base, recommendations for the Philippines should be implemented through pilot-based scale-up rather than blanket promotion. Carefully designed Philippine pilots, combining clean-plant systems, quality-focused postharvest management, and producer coordination, and accompanied by monitoring of yields, employment and biodiversity, can test which elements of the Vietnamese experience are transferable and which need to be adapted or avoided.

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