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Climate-Resilient Lychee Cultivation: Economic Analysis and Optimal Production Models for Sustainable Farming

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Abstract: The transition between lychee varieties has significantly influenced the economic dynamics of farming communities in northern Thailand. This study examines the shift between two lychee varieties and compares optimal production models under increasing climate variability. A mixed-methods approach was applied, using structured schedules with 120 lychee-farming households and in-depth interviews with seven key informants, including farmer leaders. Quantitative analysis employed descriptive statistics (frequencies, means, and percentages) to compare profitability across four production models: wrapped and non-wrapped cultivation of two lychee varieties. Qualitative data were analysed thematically to contextualise economic changes, group formation, and farmer adaptation strategies. Results show that the traditional variety, valued for fresh-market and industrial demand, incurs an average annual loss of 3,283.33 THB per household without fruit wrapping due to heat-induced pericarp browning. In contrast, wrapped production yields a net profit of 30,667 THB. The heat-tolerant variety introduced in 2017 demonstrates stronger resilience, generating 42,583.33 THB without wrapping and 39,833.33 THB with wrapping. The highest return (2,876.42 THB per rai) occurs under non-wrapped cultivation of the newer variety. An optimal strategy combines 70% wrapped traditional cultivation with 30% non-wrapped heat-tolerant production, maximising income stability. The transition has strengthened farmer cooperatives, value-added processing, and local economic circulation while maintaining traditional rural structures despite persistent household debt.

Keywords: Community Organisation; Lychee Varieties; Hong Huay Lychee; Varietal Adaptation; Fruit Bagging; Community Economy; Climate-Resilient Agriculture; Cost-Return Analysis.

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1. Introduction

Food systems worldwide are set to face unprecedented challenges, as the global population is projected to reach 10 billion by 2050 [47]. The world faces the dual challenge of feeding the population while mitigating the risks of climate change. To meet these dual challenges, global food production must escalate by approximately 60 per cent - a task rendered increasingly difficult by the degradation of natural resources and the erratic nature of bioclimatic patterns; therefore, there is an urgent need for sustainable approaches to farming that enhance productivity while protecting the natural resources [11]; [13]. Alternative

agriculture practices, because of their capacity to deliver ecological and social benefits and higher profitability, have emerged as a solution [27]. In Thailand, where smallholders face soil degradation, export pressures and climate shocks (German International Cooperation Agency), alternative methods of farming, which synthesise ecological sustainability with the collective organisation of the farmers in the form of farmer cooperatives and women's groups, have gained attention as a way to sustainable development [20]. For self-reliant farming, Ban Chan's organic enterprise uses community participation to reduce debt through shared resources that embody the community economy's ethical interdependence [89]. These dynamics make the Ban Tha Ton Hat lychee cooperatives a manifestation of community economy within Thai alternative agriculture [19].

However, empirical studies on specialised perennial crops, such as lychee, where climate vulnerability demands community-level adaptation, are limited. Neef et al. [54] review microtrade for Hmong lychee farmers (Doi Suthep-Pui, Chiang Mai) and focus only on marketing risks/prices and GAP certification, noting a decline, but do not address community adaptation analysis. Sthapit et al. [80] note that there is only limited literature available on perennial tropical fruit tree species in the context of climate change and their coping mechanisms with tropical phenological patterns, information critical for lychee's flowering and fruit set, which remains poorly understood despite advances in modelling for annuals. Climate vulnerability in northern Thai fruit systems is confirmed in recent studies. Still, empirical evidence for community adaptation remains scarce, particularly for GI-certified Hong Huay from Mae Chai/Phayao, where heat-induced losses demand collective strategies [76]. The present study addresses this gap by analysing Ban Tha Ton Hat Moo 8 (Mae Chai, Phayao), Thailand's heartland of lychee, where 120 households have transformed rice paddies into lychee orchards, forming farmers' and homemakers' groups for processing/marketing while balancing traditional (Hong Huay) and resilient (Nakhon Phanom 1) varieties. Guided by community economy theory, researchers examine how these dynamics sustain incomes amid heat stress and high market volatility. While these contextual factors highlight lychee's economic importance in Phayao Province, existing research has primarily focused on national production patterns and general agronomic challenges [1]. The following literature review synthesises prior studies on Thai lychee varietals, focusing on adaptation strategies and community economy aspects to validate the critical research gaps addressed by this study.

2. Literature Review

The global lychee (Litchi chinensis Sonn) market is entering a stage of sustained structural growth, supported by rising international demand and the growing use of lychee-based ingredients in functional foods and beverages. Recent estimates value the global lychee market at USD 7 Bn in the mid-2020s, with projected compound annual growth rates generally in the 5–6 per cent range by the early 2030s. Production and trade of lychee remain heavily concentrated in Asia, where China, India, Vietnam, Thailand, and a few other regional producers account for the majority of global supply [88]; [91]. Industry analyses show that Thailand accounts for a substantial share of total exports, where Vietnam has emerged as the leading exporter and China, along with India, continues to be a major producer, so that Asian producers collectively dominate more than four-fifths of global lychee availability [81]. There are many known cultivars in Thailand. They are divided into two groups: the lowland or tropical lychee, a group of 20 cultivars commercially grown in the central region with warm winter months, and the subtropical lychee, including the 10 hitherto known commercially grown varieties in the northern part of the country, where winter months are rather cool. Lychee, which ranks eleventh among economic fruit crops, was probably introduced by Chinese traders and seafarers around 150 years ago [51]. The species subsequently proliferated across various nations, including India, Myanmar, Taiwan, Australia, South Africa, Southern Japan, Vietnam, Cambodia, and Thailand. In the Thai context, although the exact period of introduction remains undocumented, lychee cultivation is predominantly concentrated in the Northern region [83]. This concentration is attributed to the North's distinct three-season climate comprising the summer, rainy, and winter seasons, which is conducive to its growth. In these areas, farmers and policymakers seek high-value commercial fruit crops to diversify rural economies.

Besides, its cultivation is expanding into diverse agro-ecological zones characterised by distinctive climatic features, market access, and farming systems [67]; [12]; [55]. The choice of cultivar is very important in these zones because of differences in flowering requirements, blooming, skin colour, flavour, and shelf life [7]; [6]. Its commercial production has become a driver of rural socio-economic transformation, providing employment and facilitating better income distribution and gender roles. The latest trade reports and customs data from 2024 to early 2025 show that lychee exports are valued at about $760 million, with a quantity of about 14,000 metric tonnes [5]; [24]; [9]. Against this backdrop, enquiring into how the varietal choice and lychee production and management practices affect community economies is a major concern in debates on inclusive and sustainable rural development [43]; [22]; [49]. At the same time, empirical studies from Thailand and neighbouring countries (Laos, Vietnam, and the Philippines) support that commercialisation does not weaken the local institutions; rather, it can coexist with, and strengthen cooperatives, farmer groups and customary governance systems when communities mediate markets and state policies with ethical economic practices (surplus distribution, commons management [87]; [85]; [84]. In the Thai context, the community economy has been promoted as a medium for sustainable development, especially in poverty-ridden regions with limited access to non-farm employment [4]. In the literature the most common research outputs on lychee and similar perennial fruit crops are on their various characteristics, climate sensitivity, economics of production and profitability in

different parts of the world, fruit developmental biology, livelihood impacts of its commercialisation in various parts of Southeaast Asia like Vietnam and Thailand showing consistent positive income effects, but at the same time highlighting vulnerabilities such as price volatility, intermediaries, input costs, production constraints and investment plan.

Menzel [51] provides a comprehensive description in his monograph, including papers on productivity, economics, and factors constraining production across various countries. Huang et al. [33] also address constraints in lychee production. Another strand of literature emphasising the horticultural aspects of lychee examines the yield performance, the effect of pre-harvest fruit bagging of lychee on the fruit quality, methods of packaging, shelf life of lychee varieties, postharvest management aspects, besides those dealing with the cost and profitability of the lychee farming, production and marketing, marketing performance of Global Gap certified lychee farmers in Madagascar [21]. A notable strand of literature concentrates on community resilience under agricultural commercialization emphasising that commercialisation can not only coexist with community structure but can also strengthen local institutions involving farmers by enhancing resilience, collective bargaining with private companies and state agencies, enabling farmers to coexist with professionalism and community values, negotiate with State Policies and handling the various dimensions of marketing and by enabling smallholder farmers Smallholders defy large-scale commercial consolidation by leveraging local resource access and household labour dynamics [36]. Studies also concentrate on "community making", involving the mobilisation of shared resources, the negotiation of land and water rights, and the establishment of new collective organisations, while negotiating political and economic conditions that determine community strength [63]. Moreover, in Thailand, community economy is understood as the foundation for sustainable development in regions with a high incidence of poverty and a lack of non-farm employment [90]; [58]. However, there is no scope for integrating community economy frameworks into these studies, let alone the nuances of lychee varieties and their harvest management.

Smallholder fruit commercialisation occupies an important niche within this broader debate on community economies and rural livelihoods [56]. This is because tropical fruit production is labour-intensive and organised through household farms, which form an important source of employment and income for rural households [28]. At the same time, it exposes farmers to price and climate shocks and intensifies pressures on land and natural resources. Despite the above facts, research on Thai agriculture has generally focused on climate change, demographic composition, and uneven adoption of new technologies as structural challenges to sustaining community well-being [61]. Generally, the studies' findings suggest that community-level analyses of specific cash crops are needed to understand how commercialisation interacts with demographic change, climate stress, and local institutions [15]. Lychee production systems are subject to challenges posed by climate change [50]; [92]. Besides, farmers are highly concerned about declining flowering, rising production costs, and uncertain returns under climate challenges [45]. To address the issues stated above, the recommendations are to adopt more heat-tolerant or "tropical" cultivars, and to enhance and manage irrigation and canopy management to stabilise yields [52]; [14]. In Thailand, the promotion of cultivars such as Nakhon Phanom 1 demonstrates the effectiveness of varietal innovation in regional development strategies [53]. The management technique adopted to address climate stresses in lychee cultivation is wrapping [17]; [46]; [37]. It's the social and economic implications that go beyond the field-level yields. Reviews of fruit bagging across crops show that while bagging can improve fruit appearance and life, it also increases labour demand, reshaping labour relations within households and communities [44]. Few community-level studies integrate detailed cost–return data with analysis of household income streams, indebtedness, and group-based processing and marketing [3]. The present study also fills this gap by examining how the introduction of the combination of Hong Huay and Nakhon Phanom 1 varieties and fruit wrapping has reshaped the community economy of Ban Tha Ton Hat in Phayao Province.

In the present paper, with 95.83 per cent Growers' Group membership and BCR-differentiated techniques (NP1 non-wrapped: 2.79; HH wrapped: 2.32), Ban Tha Ton checks whether profitability-driven specialisation sustains collective action beyond simple resistance paradigms [78]; [73]. There are four points of difference which distinguish this analysis: (1) perennial crops vs annual crops; (2) economic institutionality (Growers' Group vs political mobilisation); (3) technique-risk matching vs land rights; (4) survey involving n=120 farm economics vs ethnography/surveys. Thus, researchers ask: Does precision agriculture (BCR-optimised portfolios) constitute 21st-century community making? Wang and Do [97] and Sensarma and Malik [1] extend this strand by quantifying the resilience effects of commercialisation. Wang and Do [97] Thai panel (n=1,648) links crop sales to absorptive/adaptive capacities of smallholder farmers via savings diversification. In summary, the literature establishes that lychee, as a vital cash crop in northern Thailand and the global lychee market, is undergoing sustained structural growth, with Thailand maintaining a substantial share of total exports. A review of the literature shows that while extensive research has dwelt on the botanical development, yield performance, and macro-level export value of Thai lychee, notably the popular Hong Huay and other high-value varieties, there remains a critical lack of baseline information regarding community-level analysis to escalating profitability and management challenges [77]; [62]. Existing studies often overlook the socio-economic dynamics of how farmer collectives mediate climate shocks through varietal diversification and postharvest management. This study addresses these empirical gaps by analysing the Ban Tha Ton Hat community in Phayao Province and examining how the transition between the traditional Hong Huay and resilient Nakhon Phanom 1 varieties, supported by community-economy principles, sustains rural livelihoods amid intensifying heat stress and market volatility.

3. Research Gap

The existing literature on Thai lychee production documents production patterns, cultivar descriptions, agronomic challenges, yield performance, climate sensitivity, income effects, production constraints, and the like. However, three critical gaps persist in the available literature. No household-level comparisons of returns and costs for specific varieties (Hong Huay vs Nakhon Phanom 1) by technique (wrapping vs non-wrapping) have been conducted, despite widespread use of wrapping to combat pericarp browning under climate stress. There is no evidence that the optimal cultivation ratios for the two varieties have been quantified, balancing market preference for traditional Hong Huay with emerging climate-resilient selections like Nakhon Phanom 1. There is only limited integration of community economy frameworks with empirical profitability data, overlooking how cooperatives and processing groups mediate varietal adoption and risk hedging in smallholder systems. This study addresses these gaps through mixed-methods analysis of 120 Ban Tha Ton Hat households and a sensitivity-validated 70:30 ratios for Phayao Province under current climate-market conditions.

4. Significance of the Study

Studies on rural development in Thailand and other Southeast Asian countries have increasingly focused on how market-oriented agriculture interacts with community organisations, social relations, and local resource management. Ethnographic and sociological studies of commercialised communities in Northern Thailand argue that community strength is determined not only by subsistence or commercial farming, but by collective action and the capacity to negotiate political and economic conditions, including state policies and market integration [65]. It is the making of the community as a forum for collective action that strengthens communal bonds; risk-sharing and market-led diversification of farm-related activities; thus proving that the villages constitute resilient social structures capable of navigating the pressures of globalisation by developing shared institutions and access to resources through networked resistance. Furthermore, these findings emphasise that adaptation strategies must be context-specific [48]; [79]; [95]. The above perspectives echo the “community economy” concept employed in the present study, which advocates local resource use, social and cultural capital among the operators, and collective exchange systems as foundations of economic resilience [64]. In Thailand, lychee commercialisation has stimulated the formation of growers’ groups and homemakers’ processing groups, expanded employment, income circulation, and encouraged local processing of dried and value-added products, echoing patterns observed in other community-based rural development initiatives across Thailand and the region [70]. At the same time, concerns about rising household indebtedness, environmental pressures from intensified input use, and uneven integration into modern retail chains underscore the need for a nuanced analysis of how varietal and management decisions in cultivation influence not only individual profitability but also the broader community economy [39].

5. Methods

The present study employs a convergent mixed methods design to examine the economic viability and optimal cultivation patterns of the Hong Huay and Nakhon Phanom 1 lychee varieties in the Ban Tha Ton Hat community, Village Moo 8, Mae Chai District, Phayao Province, characterised by a monsoon climate with distinct dry and rainy seasons. The community in the selected area has a history of cultivating Hong Huay lychee for over 30 years, with Nakhon Phanom 1 introduced in 2017 as a climate-resilient alternative. The 2024/25 production season serves as the reference period for all cost-return analyses. With a pre tested schedule, data on demographics, production economics, climate perceptions, household finances and lychee production system of 120 households selected through random sampling from the village lychee growers’ register, ensuring proportional representation of farmers cultivating Hong Huay only, Nakhon Phanom 1 only, or both varieties, production costs, revenues, and profitability have been collected concurrently with qualitative insights on decision-making by farmers, climate adaptation strategies, and community economic dynamics. Seven key informants were selected via purposive sampling based on: (a) farming experience (>20 years), (b) leadership roles in the Lychee Growers Group or homemakers’ processing groups, (c) cultivation of both varieties, and (d) willingness to share in-depth insights.

Informants included the village headman, two cooperative leaders, three farmer representatives (one female-headed household), and one representative from the homemakers’ processing group, to ensure diverse perspectives. The integration of both data streams facilitates a holistic understanding of varietal choice under climate variability. Data were collected over six weeks, from the middle of January to the end of February 2026, by trained enumerators. Key informant interviews were conducted by the principal investigator in convenient locations. Informed consent was secured from all participants, with assurances of confidentiality. For the quantitative data analysis, descriptive statistics, Sensitivity Analysis, Benefit-Cost Analysis, benefit-cost ratio, percentage analysis, and comparative analysis of four production patterns have been used. Transcribed interviews have been analysed using thematic content analysis. Quantitative cost-return and BCR findings have been triangulated with qualitative narratives on farmer rationale, market dynamics, and climate perceptions. Points of convergence (e.g., both datasets confirming the necessity of Hong Huay’s wrapping) and complementarity (qualitatively explaining why non-wrapped Hong Huay incurs losses) strengthened the validity of the findings and conclusions.

6. Limitations

The study is cross-sectional, capturing only one production season; inter-annual yield and price variability may affect generalizability. Data from farmers are subject to recall bias. Findings are specific to Ban Tha Ton Hat's context and are limited by climatic conditions and market variations; therefore, extrapolation to other contexts requires caution.

7. Contribution of the Paper

Three specific contributions are made here. First, this paper provides the first quantified analysis comparing costs, profits and losses across two varieties of lychee, Hong Huay and Nakhon Phanom 1, with four production management techniques involving wrapping and non-wrapping using household-level data from 120 farmers in Phayao Province. Unlike prior agronomic studies, which focused on yield or quality attributes, this analysis reveals that Nakhon Phanom 1 non-wrapping yields an average profit of 24,557 THB per household (2.1× higher than bagged Hong Huay). At the same time, non-wrapped Hong Huay incurs losses of -3,283 THB, establishing clear profitability thresholds for adopting the technique. Secondly, the study proposes a context-specific cultivation ratio of 70 per cent Hong Huay and 30 per cent Nakhon Phanom 1 as an economic optimum for Phayao smallholders, balancing persistent consumer/industrial preference for Hong Huay (despite its climate vulnerability) with its superior heat tolerance and profitability. This ratio emerges directly from integrating profit data with farmer adoption patterns and market price differentials (25-80 THB/kg for Hong Huay vs 80-120 THB/kg for Nakhon Phanom 1), extending beyond varietal description to actionable farm-level guidance.

Beyond technical comparisons, this research demonstrates how varietal diversification interacts with community-level economic structures, including women's processing groups, and local income circulations. This mixed-methods approach bridges microeconomic farm data with Gibson-Graham's community-economy framework, revealing structural rather than transformative livelihood impacts. Consequently, the practice of fruit bunch wrapping has been adopted as a maintenance strategy to enhance skin colouration, increase fruit size, and extend the harvest window [25]; [26]. Although this method nearly doubles the market price of unwrapped fruit, it also entails higher operational costs. Moreover, climate change is not the sole factor influencing quality; varietal selection is equally critical. In 2017, the "Nakhon Phanom 1" variety was introduced to the community for its heat tolerance, larger fruit, drier flesh, and earlier maturation (April) compared to the "Hong Huay" variety (May). Despite these advantages, the "Hong Huay" variety remains more popular among consumers. In light of these dynamics, there is an urgent need to investigate "the optimal maintenance protocols and the appropriate cultivation ratio between the 'Hong Huay' and 'Nakhon Phanom 1' varieties." Such research is vital for the sustainable economic development and the enhancement of the quality of life for farming households in the Ban Tha Ton Hat community, Village Moo 8, Mae Chai District, Phayao Province.

8. Results of the Analysis

8.1. Community Livelihood Structure of Lychee Farmers and Cultivation Trends

Regarding the household context of farmers in Ban Tha Ton Hat, the data indicate that 39.17 per cent of respondents are aged 60 or older. This is followed by those aged 51-60 (30.83 per cent) and 41-50 (20 per cent), while the groups aged 31–40 and 21–30 each represent 5 per cent. The workforce's demographic pattern skews older: 39.17 per cent are over 60, and 30.83 per cent are aged 51-60, indicating that more than 70 per cent are over 50. Only 10 per cent are under 40. This shows vulnerability to labour shortages, reduced chances of adopting innovation (e.g., wrapping techniques), and succession risks as younger farmers decrease. The average age of lychee farmers in Thailand is 48-59 years old due to national agricultural ageing trends. This increases the MSD (Musculoskeletal Disorders) vulnerability risk, which crop-specific challenges will further magnify. In the Ong-Artborirak et al. [59] study of 404 ethnic lychee-longan workers (average age 48.8), 99.5 per cent reported MSDs in the past 7 days. Moreover, MSD is near-universal among lychee farmers compared to other cultivations such as tobacco, mango, and rubber tapping [2]. The respondents' educational levels show that 30 per cent have completed upper primary school, 25.83 per cent have completed lower primary school, 18.33 per cent have completed upper secondary school, and 15 per cent have completed lower secondary school. Only 10.84 per cent of the respondents hold a bachelor's degree or higher. The implications of the distribution of respondents by education: 55.83 have only a primary-level education (30 per cent upper primary, 25.83 per cent lower primary). With most respondents constrained to a primary level of education, their access to advanced agronomy, financial literacy, or advanced digital tools is likely to be limited, and they may have to rely on traditional Hong Huay varieties rather than the resilient Nakhon Phanom 1.

The implications of the demographic and educational level distribution of the respondents: wrapping (labour-intensive) may be challenging for older farmers, favouring low-effort NP1 non-wrapping. The results show that youth training, subsidies for labour-saving technology, or intergenerational knowledge transfer are critical for lychee sustainability in Phayao. These results align with broader trends in Thai agriculture [101]. It is seen that 95.83 per cent of the households are registered members of

the Lychee Growers' Group. The remaining 4.17 per cent are not registered because lychee cultivation is rather a supplementary source of income, leading to less engagement in community group activities. The pattern of the membership in the group shows that the group is effectively a universal platform for coordination, collective decision making and information sharing in the community, suggesting a strong social capital and high potential for group-based interventions like training, input distribution, collective marketing, GI branding, and climate adaptation measures, as almost all producers can be reached through a single organisation. This enables the community to operate as a unified economic bloc, making it easier for NGOs or government bodies to implement interventions because the infrastructure for communication and collective action is already 96 per cent complete. The 4.17 per cent who are not registered because lychee is only a supplementary source of income for them. It indicates a clear segmentation between "core lychee farmers" and "occasional lychee growers." The occasional lychee growers are likely less interested in meetings, training, or quality-control protocols. They may also be slower to adopt improved practices such as bagging/wrapping, pruning regimes, or variety shifts, e.g., towards Nakhon Phanom 1.

It may also mean that a small subset of the population is "information-poor" regarding best cultivation practices. The fact that 84 per cent of households are primarily engaged in the agricultural sector, especially lychee cultivation, indicates a lack of livelihood diversification and makes them more prone to market and climate shocks. Thus, it can be concluded that the community exhibits a monopsonistic social structure where "lychee cultivation is not [the] primary occupation" for the minority (4.17 per cent). In contrast, the vast majority (84.17 per cent) remain tethered to the agricultural sector as their lead economic driver. The high specialisation in lychee cultivation (84.17 per cent) results in structural dependence on the lychee crop, causing livelihood vulnerability, a phenomenon well-documented in Northern Thai agro-ecosystems where resource-poor populations face significant climate risks. However, the community offsets this risk through social cohesion, with 95.83 per cent participation in the Growers' Group. As Nor Diana et al. [57] suggest, such social networking is a primary adaptation strategy in Southeast Asia, explaining why even households with supplementary lychee income choose to maintain group membership - about 11.66 per cent of the households consider lychee their primary income, but are the secondary group, who only do it as a side job and find the group valuable enough to join. They might have been motivated by the social pressure, access to resources and information. The 15.83 per cent off-farm segment is dominated by low-skill general labour (7.50 per cent), which suggests seasonal or opportunistic wage work, followed by private business (5.83 per cent) and a tiny elite of government employees/officials (2.50 per cent). This pattern mirrors broader Southeast Asian rural trends, where agriculture employs 30–60 per cent of labour (e.g., Thailand ~32–44 per cent in recent data). However, off-farm households (especially business/government) may have higher risk tolerance/capital for innovations like NP1 non-wrapping, while their counterparts may prioritise stability.

Economically, the average monthly household income is 26783.42 THB (~800 USD), while the average monthly expenditure is 18436.42 THB (~550 USD). This indicates a capacity for savings. Approximately 70.86 per cent of household savings are kept as cash at home. In comparison, 29.14 per cent are deposited in financial institutions such as commercial banks or the Bank for Agriculture and Agricultural Cooperatives (BAAC). The high percentage of savings kept at home (70.86 per cent) signals low financial literacy or high liquidity preference (common in farm communities for emergencies). At the same time, 29.14 per cent of the savings kept in banks/BAAC indicates emerging formalisation. The average household debt stands at 158,375.48 THB (~4,700 USD), which equates to ~19 months' surplus, manageable but tied to post-2017 BAAC loans for Nakhon Phanom 1 (NP1) adoption, mostly originating from BAAC loans taken since 2017 for investment purposes. This period coincided with the introduction of the Nakhon Phanom 1 lychee variety, which requires capital for saplings and cultivation. Currently, the community grows two main varieties: Hong Huay and Nakhon Phanom 1. Hong Huay remains the primary variety, with most farmers having over 30 years of experience. The Nakhon Phanom 1 variety was introduced for its heat tolerance and earlier harvest cycle compared to Hong Huay. This debt-financed shift aligns with NP1's advantages: heat resilience (important in an era of climate change) and earlier harvest (80–120 THB/kg vs HH's 25–80 THB/kg), extending the income window. Usually, Hong Huay's dominance (decades of experience) provides stability/market familiarity, but NP1 hedges risks (as per the details in Table 1: NP1 profits are 20k–24k THB against HH's 3k-11k THB profit), justifying a 70:30 ratio as a debt-servicing strategy. Overall, solvency supports scaling resilient practices, but cash hoarding risks liquidity crunches during off-seasons.

8.2. Lychee Production, Cost, and Return Patterns

Table 1 presents the comparative cost and return structure for lychee production of the Hong Huay and Nakhon Phanom 1 varieties under wrapping and non-wrapping practices. The results indicate clear differences in profitability. The average production cost for Nakhon Phanom 1 ranged from THB 18,025.83 in the non-wrapping system to THB 19,109.17 with wrapping, which is slightly higher than the corresponding costs observed for Hong Huay (THB 17,450.00–18,833.33). However, the returns from Nakhon Phanom 1 are greater despite the marginally higher production. The total average return for Nakhon Phanom 1 was THB 42,583.33 under non-wrapping and THB 39,833.33 under wrapping, indicating strong market performance for this variety. Nakhon Phanom 1 has recorded the highest average profits among the production systems. The non-wrapping system yielded the highest profit (THB 24,557.50), followed by the wrapping system (THB 20,724.16). These

results suggest that Nakhon Phanom 1 is more profitable for farmers, despite slightly higher production costs. By contrast, the Hong Huay variety shows lower financial performance than its counterpart. Although the wrapping system generated a moderate profit of THB 11,833.33, the non-wrapping system resulted in a loss of THB 3,283.33, indicating that the Hong Huay variety without fruit wrapping may expose farmers to greater risk. The ranking analysis shows the relative performance of the production systems. Nakhon Phanom 1 under non-wrapping conditions ranks first in profitability, followed by Nakhon Phanom 1 with wrapping. Hong Huay with wrapping ranked third, and Hong Huay without wrapping is the least profitable system. These findings highlight the importance of varietal selection and management practices in improving farm-level income and enhancing the economic sustainability of lychee production systems. The two varieties can classify lychee production in Ban Tha Ton Hat into two techniques: Wrapping (Bagging) and Non-wrapping. Profitability across techniques applied to each variety diverges sharply. The variety Hong Huay achieves viability and profitability only through wrapping. At the same time, NP1 sustains comparable returns even without value-adds such as wrapping, confirming a complementary production logic in the mixed varietal system that balances quality, resilience, and cost efficiency.

8.2.1. Hong Huay Variety

This variety belongs to the "Tai So" group of lychee cultivars, which is a relatively large, heart-shaped fruit with a pericarp featuring dense, sharp-pointed protuberances. Despite its high yield potential, as its skin lacks a robust protective cuticle compared to other varieties, the fruit is exceptionally sensitive to ambient temperature fluctuations. Exposure to direct sunlight results in rapid water loss from the pericarp of Hong Huay. The sensitivity of Hong Huay is so severe that exposure to high temperatures turns the fruit dark, making it unmarketable within a very short window. This vulnerable feature is the primary driver behind the adoption of wrapping techniques, which 58.33 per cent of farmers utilise to maintain skin quality [93]; [71]; [42]. In contrast, the Nakhon Phanom 1 (NP1) variety demonstrates greater weather resilience. NP1 has a Geographical Indication (GI) in Thailand, recognised for its distinct physical characteristics, including a more durable skin and an "egg-shaped" morphology. The physiological features of NP1 provide a natural adaptation to the intense heat and humidity characteristic of Nakhon Phanom province and confer inherent resilience, as it can maintain skin colour and fruit integrity even under thermal stress that would degrade the Hong Huay variety. Because of these properties, NP1 does not require the same intensive care as Hong Huay, and farmers can choose management techniques based on economic factors rather than biological necessity.

The study finds that 58.33 per cent of farmers prefer the wrapping technique, while the remaining 41.67 per cent do not wrap. Wrapping is chosen because it maintains skin quality. Hong Huay's skin sensitivity makes it vulnerable to heat and sunlight, which can cause the fruit to turn dark and become unmarketable; therefore, the farmers choose to wrap it. As per Table 1, farmers using the wrapping technique earned an average net profit of 30,667.00 THB in the previous production year. Conversely, those who opted not to wrap suffered an average loss of 3,283.33 THB; thus, there is a binary outcome for wrapping. The profit is attained by securing a higher percentage of high-quality fruit that meets the visual standards of high-end retail and export markets, and the loss represents a total failure to recover the fixed costs, which include irrigation, fertilisation, and pest management. For example, maintaining a lychee tree often requires 200–300 litres per tree per week during the flowering and fruiting stages. When lychee becomes unmarketable due to skin darkening, these investments are entirely lost [16]. The profitability equation of HH (Hong Huay Variety) is:

- **With wrapping:** $P_{HH(wrap)} = (Y_{wrap} \times Q_{iHH(wrap)} \times P_r) - (C_{(wrap)} + C_{(fixed)})$
- **Without wrapping:** $P_{HH(non)} = (Y \times Q_{HH(non)} \times P_r) - (C_{(fixed)})$

Where:

- $P_{HH(wrap)} =$ Profit of HH with wrapping
- $Y_{HH(wrap)} =$ Yield of HH with wrapping
- $Q_{HH(wrap)} =$ Quality index of HH with wrapping (higher with wrapping);
- $P_{rHH(wrap)} =$ Market Price of HH with wrapping
- $C_{HH(wrapp)} =$ Cos of wrapping of HH
- $C_{(fixed)} =$ Fixed cost of cultivation

The divergence in farmer behaviour regarding the choice to wrap or not wrap fruit despite the risk of loss can be attributed to broader socio-economic factors as key determinants of postharvest management adoption (e.g., wrapping or not wrapping) in lychee and other perishable fruits [60]. The study identifies household and farming characteristics, age and innovation, labour and market constraints, and participation in agricultural cooperatives as the major drivers of postharvest loss-causing decisions [40]; [34]; [72]. Household and farming characteristics, storage facilities, and market access all influence postharvest decisions

and, in turn, profitability [41]. Besides, the farmers may opt not to wrap the fruits due to unavailability of skilled labour, financial constraints, low levels of education and good management practices, and lack of market information [38]; [29].

8.2.2. Nakhon Phanom 1 Variety

For this variety, both wrapping and non-wrapping systems are profitable, with non-wrapping showing slightly higher average profit. Since the analysis is based on aggregated cost and return data, statistical significance between the two practices has not been evaluated. Nakhon Phanom 1 (NP1) is a superior economic model because of its genetic resilience rather than human intervention. Unlike the Hong Huay variety, which is highly thermally sensitive, NP1's status as a weather-resilient Geographical Indication (GI) product enables it to maintain quality without incurring the additional cost of wrapping. Both methods yield an average of 200.00 kg per tree. Nakhon Phanom 1 is more weather-resilient and requires less meticulous care than Hong Huay. Since the yield remains constant at 200 kg per tree regardless of the preharvest care method, the labour and material costs associated with wrapping provide no additional biological benefit and can therefore be avoided. This makes wrapping a "value-destructive" activity for this variety, resulting in a loss of nearly 2,000 THB per rai and negative marginal utility from wrapping. The GI certification of NP1 is a quality assurance mechanism that allows farmers to command premium prices (it addresses the information asymmetry between farmers and consumers) based on the variety's reputation for large size and distinct flavour, rather than relying on the artificial aesthetic protection required by more fragile cultivars. In the past year, the non-wrapping technique generated an average income of 42,583.33 THB, while wrapping generated 39,833.33 THB. In terms of net profit, non-wrapping yielded nearly 2,000 THB more per rai than wrapping, as it avoids the additional costs of materials and labour. Besides, non-wrapping is the optimal strategy for NP1 because it mitigates the impact of labour shortages and high material costs, which are the primary causes of postharvest economic losses for small farmers. Towards the conclusion, it can be stated that the 33,950.33 THB profit differential for Hong Huay represents an extreme "quality trap" associated with sensitive varieties, as without protection, they are liabilities rather than assets.

On the other hand, there is an inverse relationship between a variety's resilience and its labour demand. High Sensitivity - Hong Huay- requires manual intervention (wrapping) to artificially reduce heat stress, creating a dependency on seasonal labour, which is increasingly scarce and expensive. In the case of high-resilience NP1, protection is provided by its own physiology (thick skin). This biological property replaces manual labour, allowing the farmer to capture more of the revenue as net profit. Modern dietary habits and the growing health consciousness of tech-savvy middle-class youth are driving the growth of the exotic fruit market. Studies show that these consumers prioritise not only flavour but also nutritional value and appearance [18]; [96]. Further, urban consumers tend to prefer to buy high-value fruit varieties with attributes such as freshness, quality, and safety when making purchasing decisions [98]; [100]. These trend facts suggest that fruit varieties with better postharvest robustness and consistent quality during transport are more likely to attract expansion in urban markets. The robustness of NP1 during transport helps the fruit reach urban markets in a better state. The consistent growth in high-value variety preferences indicates that NP1 is better positioned to capture the burgeoning middle-class market than Hong Huay, which is more fragile. The comparative analysis of both varieties provides a clear indication of the region's agricultural strategy. The Hong Huay variety requires mandatory wrapping, with a significant profit difference of nearly 34,000 THB between wrapped and non-wrapped harvests. Its thin skin and heat sensitivity make it a high-risk variety. Nakhon Phanom 1, due to its natural resilience to weather and GI status, offers a more robust and efficient economic model. As the yields of 200.00 kg per tree with/without wrapping are the same, NP1 farmers can maximise their net profit by minimising labour and material costs. The income of 42,583.33 THB for non-wrapped NP1 suggests that genetic resilience is the most effective tool for long-term farm profitability.

Table 1: Costs and returns of lychee production patterns between Nakhon Phanom 1 and Hong Huay varieties

Cost/Return	Nakhon Phanom 1		Hong Huay	
	Wrapping	Non-Wrapping	Wrapping	Non-Wrapping
Average Production Cost (THB)	19,109.17	18,025.83	18,833.33	17,450.00
Total Average Return (THB)	39,833.33	42,583.33	30,667.00	14,166.67
Average Profit (THB)	20,724.16	24,557.50	11,833.33	(-3,283.33)
Rank	2	1	3	4

8.3. Sensitivity Analysis

Sensitivity analysis assesses the robustness of lychee production profitability even in the face of possible fluctuations in prices and production costs. The analysis is conducted by simulating changes in key economic variables, such as the cost of production and market price, while holding other factors constant. Two scenarios are considered: (i) a 10 per cent decrease in output price and (ii) a 10 per cent increase in production cost. Additionally, a combined scenario that incorporates both price reduction and cost increase is evaluated to represent adverse market conditions. The following relationships are evaluated to estimate the net return (profit) under each scenario:

- Profit $=$ Total return $-$ total cost

If there is a price shock of a reduction by 10 per cent:

- New return $=$ Base return $\times (1 - 0.10)$

For the cost shock scenario:

- Newcost $=$ Base Cost $\times (1 + 0.10)$

8.3.1. Sensitivity Index

A Sensitivity Index (SI) has been calculated to quantify the responsiveness of profitability to changes in economic variables, such as sales revenue and costs:

$$\text{SI} = \frac{\%\text{ change in profit}}{\%\text{ change in price or cost}}$$

The Sensitivity Index provides information about the degree to which profitability is affected by variations in these parameters (Table 2):

- **SI** >1 indicates high sensitivity of profit to the variable.
- **SI** =1 indicates proportional responsiveness.
- **SI** < 1 indicates relatively low sensitivity.

Table 2: Results of sensitivity analysis of profitability under price and cost shocks in lychee production

Production System	Profit (THB)	Profit Underprice −10% (THB)	Profit Under Cost +10% (THB)	Profit Under Price and Cost +10% (THB)	SI (Price)	SI (Cost)
Nakhon Phanom 1 – Wrapping	20,724.16	16,740.83	18,813.24	14,829.91	1.92	0.92
Nakhon Phanom 1 – Non-wrapping	24,557.50	20,299.17	22,754.92	18,496.59	1.73	0.73
Hong Huay – Wrapping	11,833.33	8,766.97	9,950.34	6,883.98	2.59	1.59
Hong Huay – non-wrapping	−3,283.33	−4,700.00	−5,028.33	−6,445.00	−4.31	5.31
Source: *Primary data*						
Notes: *1. Prices correspond to the market purchase prices for the 2023/24 production season 2. The average selling price for the Hong Huay variety was 25-80 THB/kg, whereas the average selling price for the Nakhon Phanom 1 variety was 80-120 THB/kg.*						

8.3.2. Interpretation

The analysis reveals that the profitability of lychee production is more responsive to changes in price than to changes in cost; the Sensitivity Index values for price changes are greater than one for most production patterns, indicating that a 10 per cent decline in output price leads to a more than proportional reduction in profits. This effect is pronounced in the Hong Huay variety when wrapped, with a Sensitivity Index of 2.59, indicating a high vulnerability to market price fluctuations. In contrast, the Sensitivity Index values for cost increases are lower for the Nakhon Phanom 1 variety, indicating its greater resilience to cost increases. The Hong Huay variety has weaker economic stability because it is more sensitive to cost changes. Furthermore, the Hong Huay non-wrapping system remains economically unviable under all scenarios. Overall, the results suggest that the Nakhon Phanom 1 variety, particularly under non-wrapping conditions, demonstrates greater economic resilience. In contrast, the Hong Huay variety is more susceptible to adverse market and cost conditions.

8.4. Qualitative Insights: Climate Vulnerabilities and Socio-Economic Benefits

Furthermore, the results of the in-depth interviews on appropriate cultivation patterns for the Nakhon Phanom 1 and Hong Huay lychee varieties indicate that lychee cultivation not only increases household income but also fosters community cooperation through agricultural cooperatives and homemakers' processing groups [31]. This is evident in the formation of agricultural collectives and homemakers' groups established for food processing, and is in line with the findings of Neef et al. [54]. Local

women's groups have started processing lychee into value-added products, creating additional income streams and fostering collaboration to build bargaining power and savings [74]. It can be surmised that perennial tree crops often encourage group formation, often into cooperatives, enhancing rural household welfare, facilitating processing into value-added products, strengthening collaboration between farmers, and enhancing income and local enterprise development [35]. Such groups typically organise joint marketing, processing (drying, juice, sweets), and savings/credit schemes, which enhance bargaining power and resilience beyond what individual farmers could achieve, especially in terms of gender roles [23]. Nevertheless, current lychee production in the community faces significant climate-related challenges. Climate change, particularly rising temperatures, poses a severe threat to the Hong Huay variety, which ripens in summer and is highly susceptible to heat damage. Additionally, water scarcity in remote, high-altitude plantations affects both yield quantity and quality. Consequently, some farmers have become increasingly aware of the need to adapt by switching to the Nakhon Phanom 1 variety, which is more resilient to the current hot climate. Although it has a less intense aroma and flavour than Hong Huay, Nakhon Phanom 1 requires less meticulous care, offers higher yields, matures faster, and has received a positive market response [99].

Regarding the economic dimension, the introduction of these two varieties allows the community to produce over 1,000 tons of lychee annually, generating substantial income and employment. NP.1 matures approximately four weeks before the market is flooded with the Hong Huay variety. This early window allows farmers to secure higher retail prices, up to 75 per cent above those of mid-season varieties. In terms of collective organisation, the study found that farmers have formed groups that exemplify classic community-enterprise models in rural Thailand, where farmer groups aggregate produce into value-added products for broader markets and year-round sales to mitigate the impact of falling prices. Residents of Moo 6 and Moo 8 have established homemakers' groups and cooperatives independently of external investment. These initiatives distribute income beyond harvest season and build social capital, aligning with earlier findings that 95.83 per cent of growers' group membership fosters cooperation. They process lychees into products such as lychee juice and lychee paste, thereby facilitating broader income distribution. Furthermore, government agencies such as the District and Provincial Agricultural Offices, along with the University of Phayao, provide knowledge and support for value-added processing, such as dried lychees for export. From a socio-cultural perspective, the introduction of these lychee varieties has integrated new social and cultural knowledge from government and private sectors into traditional production methods. This has increased community participation and modernised agricultural practices to better suit local lifestyles, ensuring long-term sustainability for local farmers. This integrated learning process—evident in extension programs promoting NP.1 resilience and processing techniques has elevated the roles of the local women through homemakers' groups, fostering gender-inclusive value chains common in hai fruit clusters.

This has enhanced community participation and modernised agricultural practices to better suit local lifestyles, ensuring long-term sustainability for local farmers. In the commercial sector, the expansion of lychee cultivation in Ban Tha Ton Hat (Moo 8) has boosted income circulation and transformed sales models. Rather than farmers transporting goods themselves, external buyers now collect produce directly. Additionally, climate-induced yield volatility has driven a shift toward processed products for economic survival and toward online marketing, expanding the customer base and increasing revenue. Regarding resources, farmers have adapted their cost management to suit the local terrain. There is a noticeable reduction in irrigation fuel consumption as farmers' transition to alternative energy sources, such as electric water pumps. However, those in remote areas without electricity still rely on traditional fuels. Thailand's solar/electric pump subsidies have cut irrigation costs by 40 to 60 per cent in areas with grid access, but gaps in remote areas persist, exacerbating water scarcity. Changes in natural resources are also evident, specifically the conversion of rice paddies into lychee orchards and declining soil quality due to increased chemical use. Paddy-to-perennial shifts boost incomes 2–3x but risk soil acidification/erosion without Integrated Pest Management, a strategy that combines multiple pest control tactics [86]. In summary, lychee cultivation has significantly transformed the economy of Ban Tha Ton Hat (Moo 8), particularly regarding household income and expenditure. However, it has also impacted the environment through the use of chemicals.

When considering the most suitable variety for the area, although Nakhon Phanom 1 is a climate-resilient alternative, it remains less popular than Hong Huay due to its inferior taste and aroma. Nevertheless, as shown in the cost Table, Nakhon Phanom 1 does not require "cluster wrapping," whereas Hong Huay does. Despite the market's preference for Hong Huay, its production is constrained by its heat sensitivity, leading to supply shortages. While Nakhon Phanom 1 is gaining traction, it cannot yet match the consumer demand for Hong Huay. Therefore, based on income data, returns, and farmer perspectives, the optimum cultivation ratio is 70 per cent Hong Huay to 30 per cent Nakhon Phanom 1. This balance is recommended because Hong Huay remains the preferred choice for consumers, wholesalers, homemakers' groups, and industrial factories for export and processing. Conversely, Nakhon Phanom 1 serves as a vital source of income protection against climate-induced losses in Hong Huay production. While the findings of the in-depth interviews demonstrate that community collectives and homemakers' groups provide the essential social infrastructure for climate adaptation and value-added processing shaping lychee systems in Ban Tha Ton Hat Moo 8, the long-term viability of these organisations depends on their measurable economic performance. To move beyond social capital and evaluate the actual financial sustainability of these efforts, the cost-benefit analysis of 2023/24 production data provides empirical evidence of their economic viability. The following Table 3 employs a Benefit-Cost Ratio (BCR) analysis (costs, returns, and profits per rai (1,600 m^2). This metric is the standard scientific tool for

determining whether specific cultivars and management practices, such as fruit wrapping, reach the threshold of 'acceptability' and high profitability required for commercial adoption in the region.

Table 3: Benefit-Cost analysis

Lychee Variety	Management Practice	Total Return (THB/rai)	Cost of Production (THB/rai)	BCR	Rank
Nakhon Phanom 1	Wrapped	4,758.59	3,474.39	1.37	4
Nakhon Phanom 1	Non-Wrapped	9,153.66	3,277.42	2.79	1
Hong Huay	Wrapped	6,233.41	2,690.48	2.32	2
Hong Huay	Non-Wrapped	5,091.92	2,462.86	2.07	3
Source: *Primary data;* ***Not:*** $BCR = \frac{Total\ returns}{Total\ production\ cost}$					

The interpretation of the Benefit-Cost analysis is provided in Table 4. Shaha et al. [75] identify a Benefit-Cost Ratio (BCR) of 2.04 as the benchmark for determining that a lychee production project is acceptable and highly profitable. The study's logic is that while any BCR greater than 1.0 can be considered profitable and sustainable, a 2.0 threshold serves as a critical indicator of highly rewarding commercial viability. A ratio of 2.04 indicates that for every 1 unit of currency invested, the enterprise returns more than double that amount, which justifies its adoption by smallholders. The benchmark details are in Table 4.

Table 4: Summary of benchmark logic

BCR	Economic Status	Decision
< 1.0	Loss	Rejected; The project is a "bad investment option."
1	Break-even	Critical threshold; no surplus, no loss.
1.1 – 1.9	Marginal	Acceptable in stable economies but avoided by smallholders due to high risk.
> 2.0	Highly Profitable	Benchmark for Success. Provides the risk premium for widespread adoption.

Table 3 presents a cost-benefit analysis of four lychee production patterns across two varieties, such as Nakhon Phanom 1 and Hong Huay, along with two management techniques - wrapped and non-wrapped. The analysis reveals marked differences in profitability driven by variety-technique interactions, with BCR values ranging from 1.37 (marginal viability) to 2.79 (excellent returns). Nakhon Phanom 1 non-wrapped achieves the highest profitability (BCR=2.79, Rank 1), generating 179 per cent ROI (ROI (%) = (BCR−1) ×100). At the same time, the same variety with wrapping produces the lowest BCR (1.37, Rank 4), indicating that wrapping is counterproductive for resilient varieties. Although none of the alternatives is without profit, variety Nakhon Phanom 1, when wrapped, yields a BCR of only 1.37. It must be viewed against the backdrop that smallholder farmers, such as those in Mae Chai District, are typically risk-averse. Though BCRs greater than 1 are mathematically profitable, they leave virtually no room for a casualty. In the case of perennial crops like lychee, several factors like climatic aberrations involving sudden heat waves, abnormal rains, or blind years (failure to blossom) can instantly cause a 20 per cent to 100 per cent reduction in annual yield, price volatility and labour shortages (causing a hike in labour cost) can erode the already narrow profit margin. On the contrary, a BCR of at least 2.0 (receiving 2 THB for every 1 THB spent) provides a financial buffer, ensuring that even if yields or prices drop by 30–40 per cent, the farmer will not suffer a net loss.

9. Discussion

The findings of this study reveal a complex interplay between lychee variety choice and community economic structures in the Ban Tha Ton Hat lychee-cultivating community. Three themes are emerging from the analysis: (1) the differential economic performance of two varieties of lychee - Nakhon Phanom 1, which is the climate resilient variety and Hong Huay, the climate-sensitive variety under alternative management regimes of wrapping and non-wrapping of the fruit (2) the role of community-based organisations in mediating market integration and managing risk, and (3) the trade-offs between market preferences and climate resilience in shaping optimal cultivation portfolios of both the types of lychee. The Benefit–Cost analysis shows that the economic viability of lychee cultivation depends on varietal selection and pre-harvest management decisions. The difference in profitability between Hong Huay and Nakhon Phanom 1 confirms that climate-resilient varieties can serve as economic buffers against climatic challenges. The non-wrapped Hong Huay system's loss of 3,283.33 THB per household represents not merely foregone profit but a complete failure to recover fixed cultivation costs. This finding extends prior research on lychee heat sensitivity [32]; [94]. It must be noted that Nakhon Phanom 1's 24,557.50 THB profit without wrapping is 2.1 times higher than the profit of bagged Hong Huay, which supports the rationale for the community's post-2017 varietal diversification. The BCR of 2.79 for non-wrapped NP1, well above the 1.72 identified by Shaha et. al. [75], suggests that this production model provides sufficient buffer against the yield and price volatility. However, the market price differential favouring Hong Huay

(25–80 THB/kg versus 80–120 THB/kg for NP1) indicates that climatic suitability alone does not determine adoption trajectories; consumer preferences and processing industry specifications continue to anchor demand for the traditional variety despite its thermal liability.

The divergent economic returns to wrapping across the two varieties illuminate the conditional nature of adaptation technologies. For Hong Huay, wrapping is a mandatory investment to prevent loss, transforming an unprofitable system into one that yields profit. The 34,116.33 THB profit differential between wrapped and non-wrapped Hong Huay underscores that, for thermally sensitive cultivars, protection costs are not optional but represent the minimum threshold for effective marketing. Conversely, the negative return to wrapping for NP1 shows that the suitability of the technology is variety-specific. This finding contradicts blanket extension recommendations promoting fruit bagging and aligns with research emphasising context-specific adaptation strategies [8]; [10]; [30]. The negative marginal utility of wrapping NP1 can be attributed to two factors: (1) the variety's inherent heat tolerance obviates the protective function that justifies the technique, and (2) the GI certification allows farmers to get premium prices rather than aesthetic enhancement. This suggests that one-size-fits-all packages may misallocate scarce farmer capital and labour. The sensitivity analysis further reveals that profitability is more responsive to price shocks than to cost changes (SI for price > 1 for most systems), with wrapped Hong Huay exhibiting extreme price sensitivity (SI = 2.59). This vulnerability stems from narrow profit margins in labour-intensive, climate-sensitive production systems. It supports findings from other export-oriented fruit value chains where smallholders bear disproportionate market risk [82]. The resilience of NP1 non-wrapped profitability to both price and cost shocks is the best option for risk-averse smallholders facing capital and labour constraints.

9.1. The 70:30 Cultivation Ratio: Balancing Market Demand and Climate Risk

The recommended 70 per cent Hong Huay (wrapped) to 30 per cent Nakhon Phanom 1 (non-wrapped) ratio represents an empirically supported suggestion to reconcile three conflicting pressures: 1. persistent consumer and industrial preference for Hong Huay, 2. the variety's climate vulnerability, and 3. the superior profitability and resilience of NP1. This portfolio approach differs from binary varietal substitution models and instead reflects a risk-hedging strategy consistent with diversification logic observed in other climate-stressed agricultural systems. The 70 per cent allocation to Hong Huay maintains a market for the community's fresh and processed lychee products. But complete reliance on this variety would expose households to catastrophic losses in heat-stress years. The 30 per cent NP1 buffer ensures income stabilisation through its early April harvest window before Hong Huay floods the market in May, climate insurance, as the variety is heat- tolerant and labour flexibility, since non-wrapped production reduces peak-season labour demand a critical consideration in an ageing farming population (average age 48–59 years) with 70 per cent of cultivators over 50. However, the optimal ratio may shift as the effects of climate change intensify.

9.2. Community Organisation and the Lychee Economy

The study's qualitative findings confirm that the transition from Hong Huay to a dual-variety system has been mediated by strong community-level institutions, particularly the Lychee Growers' Group (95.83 per cent membership) and homemakers' processing groups. The near-universal Growers' Group membership creates a platform for rapid diffusion of adaptation knowledge, collective bargaining with traders, and coordination of post-harvest timing to avoid price fluctuations, especially, depressing market gluts. This finding supports evidence that market integration can coexist with, and even strengthen, local institutions when communities retain organisational autonomy and control over value-chain positioning [68]; [66].

The processing groups formed by homemakers are important because they extend lychee income beyond the 6–8-week harvest window by producing juice, paste, and dried products for year-round sale. These groups facilitate the redistribution of income to women, address gender disparities in agricultural earnings, and enhance household resilience through diversified income streams. These groups are formed without external donor funding, suggesting a genuine community demand for these institutional arrangements rather than top-down imposition. There is financial fragility underlying the apparent prosperity, as evidenced by the persistence of substantial household debt. There are labour constraints and succession risk as the demographic profile of Ban Tha Ton Hat's lychee farmers, 70 per cent over age 50, 39.17 per cent over 60, with only 10 per cent under 40, poses a long-term threat to the sustainability of labour-intensive cultivation practices like wrapping. The low educational attainment of the farming population (55.83 per cent with only primary education) further limits the adoption of more sophisticated adaptation strategies. The conversion of rice paddies to lychee orchards in Ban Tha Ton Hat has profound environmental implications. Perennial fruit cultivation involves intensified agrochemical use, which has contributed to declining soil quality and potential soil acidification. Shifting away from perennial crops alters hydrological regimes, as lychee orchards require irrigation patterns different from those of flooded rice fields.

9.3. Community Economy Implications

The study's findings reveal both the strengths and limitations of the community economy framework for understanding Ban Tha Ton Hat's transformation. On the positive side, the near-universal Growers' Group membership, cooperative processing initiatives, and local capital circulation demonstrate that collective institutions mediate market engagement, redistribute benefits beyond primary producers (e.g., to women through processing groups), and build adaptive capacity. The communities formed for cultivation in the area differ from those formed by the cabbage farmers, who mobilised against state forest encroachment. Ban Tha Ton Hat's collective action centres on economic institutionality [69].

9.4. Structural Livelihood Change

Lychee commercialisation has produced structural livelihood impacts, such as increased income, cooperative formation, and gender inclusion through processing groups, but not transformative change; there are no alterations to rural settlement patterns or occupational composition. No substantial urbanisation or out-migration has occurred; the community remains 84.17 per cent dependent on agriculture as its primary source of income. This pattern contrasts with rural-urban migration models, in which agricultural commercialisation drives occupational diversification, non-agricultural enterprise growth, and a demographic transition toward service and manufacturing economies. Several factors may be responsible for this phenomenon. Lychee cultivation is sufficiently profitable (monthly household income of 26,783.42 THB) to discourage migration to urban areas, particularly given Thailand's rising urban living costs and stagnant wages for low-skilled migrants. Second, perennial crops create sunk costs, as farmers have invested in orchards that will produce for decades, thereby reducing incentives to abandon agriculture. Third, cultural attachment to land and community, reinforced by cooperative institutions, may exert non-economic retention effects. Finally, limited educational attainment (55.83% primary only) constrains occupational mobility, as urban labour markets increasingly demand secondary or tertiary credentials. The structural persistence seen in Ban Tha Ton Hat is positive or negative, impact-wise, which is a debatable point. From a community economy perspective, maintaining rural livelihoods and local institutions is a positive outcome because it avoids the social dislocation and inequality often accompanying urbanisation. On the contrary, continued agricultural dependence perpetuates vulnerability to climate and market shocks. The study cannot adjudicate this debate but clarifies that Ban Tha Ton Hat's trajectory differs from linear urbanisation models.

10. Conclusion

This study examined the economic pathways arising from the transition between Hong Huay and Nakhon Phanom 1 lychee varieties in the Ban Tha Ton Hat Moo 8 community, Thailand, using mixed-methods data from 120 households and 7 key informant interviews. The research highlighted profitability differentials across four production systems (wrapped and non-wrapped Hong Huay; wrapped and non-wrapped Nakhon Phanom 1). The analysis shows that the Nakhon Phanom 1 non-wrapped option is the most profitable and resilient system, demonstrating that genetic climate resilience can substitute for labour-intensive post-harvest interventions. Sensitivity analysis reveals that profitability is more responsive to price shocks than to cost increases, underscoring the importance of diversification strategies. The study therefore proposes a 70 per cent Hong Huay (wrapped) to 30 per cent Nakhon Phanom 1 (non-wrapped) cultivation ratio as an economic optimum. Lychee cultivation has generated substantial livelihood impacts, including an average monthly household income of 26,783 THB, the formation of the Lychee Growers' Group, with 95.83 per cent membership, and the establishment of homemakers' processing groups producing value-added products. The community remains 84.17 per cent dependent on agriculture, and traditional rural patterns persist. Thus, there is structural persistence, reflecting the profitability of lychee cultivation, which discourages out-migration. The study makes three contributions. It quantifies cost-return analysis comparing lychee varieties and management techniques at the household level in Thailand for the first time. It establishes clear profitability thresholds (BCR 2.79 for NP1 non-wrapped vs 1.37 for NP1 wrapped vs 2.32 for HH wrapped vs 2.07 for HH non-wrapped) that help inform adoption decisions. It proposes a context-specific cultivation ratio grounded in empirical profit data.

It shows how commercialisation can coexist with, and sometimes strengthen, local institutions when communities retain organisational autonomy. However, the study also reveals challenges and vulnerabilities that complicate narratives of successful adaptation. The magnitude of household debt, averaging 158,375 THB and largely tied to BAAC loans for post-2017 NP1 adoption, results in financial fragility, with repayment crises possible if prices collapse or production fails. The ageing farmer population and near-universal prevalence of musculoskeletal disorders threaten the sustainability of labour-intensive wrapping practices, requiring accelerated shifts toward low-labour NP1 systems or mechanisation investments. The implications are that services must be context-specific rather than offering blanket technical recommendations. Future research should address the study's limitations by using longitudinal panel designs to track varietal transition outcomes across multiple seasons and climatic conditions, clarifying whether profit differentials persist or erode as NP1 adoption becomes widespread. The community's success in navigating the Hong Huay to Nakhon Phanom 1 transition while maintaining social cohesion, generating substantial income gains, and preserving rural livelihoods demonstrates that smallholder adaptation to climate change is not merely a

technical matter of varietal substitution or agronomic adjustment, but a socio-economic process mediated by community institutions, market structures, and policy environments. The 70:30 cultivation ratio proposed here is not a static suggestion but an adaptive heuristic that requires ongoing adjustment as climate, markets, and technologies evolve. What remains constant is the imperative for diversification.

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