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Economic viability of high-density pineapple farming models on marginal acidic lands: A smallholder perspective

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Abstract

Pineapple growers across Central America's acid lowlands face a widening profitability squeeze as input costs climb faster than farm-gate prices. Raising planting density from the conventional 43,500 plants ha⁻¹ to 65,000 plants ha⁻¹ has been proposed as a pathway to higher per-hectare revenue, but its economic performance on marginal acid soils where additional liming and fertility inputs are mandatory has not been rigorously assessed from the smallholder viewpoint. This research compared high-density (HD, 65,000 plants ha⁻¹) and conventional density (CD, 43,500 plants ha⁻¹) MD2 pineapple production systems on a Typic Hapludult (pH 4.3) near Pital de San Carlos, Costa Rica, over two consecutive cropping cycles (June 2018–October 2021). Enterprise budgets were constructed from actual input costs, labour records, and harvest data collected from 12 paired plots (6 HD, 6 CD), each 0.25 ha. Benefit-cost ratios (BCR), net present value (NPV at 8 % discount rate), internal rate of return (IRR), and payback period were calculated under optimistic, base-case, and pessimistic price scenarios. HD plots produced 78.4 t ha⁻¹ across the two cycles versus 52.1 t ha⁻¹ for CD, a 50.5 % yield advantage that more than compensated for the 46.3 % higher total production cost (USD 2,180 vs. 1,490 ha⁻¹ in the final year). Base-case BCR was 1.92 for HD and 1.38 for CD; NPV over the project horizon was USD 3,210 ha⁻¹ for HD versus USD 1,140 ha⁻¹ for CD. Even under pessimistic pricing (farm-gate at USD 0.08 kg⁻¹), HD maintained a BCR above 1.47, while CD dropped to 1.12. These results indicate that high-density pineapple farming on marginal acid soils is economically viable for smallholders provided that initial liming and sucker costs are financed, and that the model holds promise as a land-use intensification strategy for otherwise underproductive acidic terrains.

Keywords: High-density planting, pineapple economics, smallholder farming, marginal acidic soils, benefit-cost analysis, net present value, internal rate of return, md2 pineapple, costa rica, land-use intensification

Introduction

For most of the twentieth century, pineapple cultivation in Costa Rica followed a straightforward path: clear forest or pasture, plant at moderate density, harvest, and repeat. By the early 2000s, however, the most productive volcanic soils near the Caribbean lowlands had already been converted, pushing expansion toward the less fertile acid Ultisols and Inceptisols of the Northern Zone, where pH values sit between 4.0 and 4.8 and exchangeable aluminum can exceed 1.5 cmol kg⁻¹ [1]. On these marginal soils, yields under conventional spacing (43,500 plants ha⁻¹) routinely fall 25–35 % below the national average, leaving smallholder growers typically farming plots of 1–5 ha struggling to cover rising input costs [2].

High-density planting (60,000–70,000 plants ha⁻¹) has emerged as one possible escape from this yield trap. By packing more plants per hectare, total fruit tonnage increases even if individual fruit weight drops slightly, and the tighter canopy suppresses weeds, potentially reducing herbicide expenditure [3]. Large-scale exporters in Costa Rica have already adopted densities of 65,000–72,000 plants ha⁻¹ on their best soils, but smallholders on acid margins have been slow to follow, citing higher sucker costs, uncertain returns, and the added expense of lime required at establishment [4]. Whether the revenue gain from extra tonnage offsets these added costs on acid soils where both lime and supplementary phosphorus represent non-trivial expenditures has not been answered with on-farm economic data.

Previous economic analyses of pineapple density trials have focused on well-buffered soils in Hawaii and Queensland, where liming costs are negligible, making their conclusions difficult to transfer to the acid-soil context [5]. A single Vietnamese trial on acid sulfate soils compared two densities but reported only agronomic rather than financial outcomes [6]. The gap in economic evidence for acid-soil settings is consequential because Costa Rica's National Pineapple

Programme is actively encouraging smallholders to intensify rather than expand, and without reliable viability data the recommendation rests on assumption rather than evidence^[7].

This research addresses that gap by constructing full enterprise budgets for HD and CD systems on a representative acid Ultisol over two consecutive cropping cycles, applying standard capital budgeting metrics BCR, NPV, IRR, payback period under three price scenarios to capture the financial risk profile that a smallholder decision-maker actually faces. The historical dimension is worth noting: Costa Rica shifted from a primarily smallholder-driven pineapple sector in the 1970s to one increasingly dominated by corporate estates after trade liberalisation in the 1990s, and the economic viability of density intensification on acid soils is one lever that could slow that consolidation by keeping small farms competitive^[8].

Climatic and environmental conditions

The trial site (10°28 N, 84°16 W, 108 m a.s.l.) near Pital de San Carlos experiences a humid 'tropical climate with mean annual rainfall of 3,420 mm distributed bimodally (peaks in June and November) and a brief drier spell from February to April. Mean daily temperature ranges from 23.8°C (January) to 27.6°C (May), with relative humidity consistently above 82 %. Soil temperature at 10 cm depth averaged 25.4°C. During the trial period, annual rainfall was 3,187 mm (2018), 3,541 mm (2019), 3,328 mm (2020), and 3,476 mm (2021, through October). No extreme drought or flood events occurred. The site receives approximately 1,820 hours of sunshine per year, and photosynthetically active radiation (PAR) averages 32.4 mol m⁻²d⁻¹ during the wet season and 41.7 mol m⁻² d⁻¹ during the drier months.

Material and Methods

Material

MD2 pineapple suckers (250–300 g) were purchased from a certified nursery in Limón Province at CRC 45 per sucker (approximately USD 0.074 at 2018 exchange rates). Dolomitic lime (52 % CaCO₃, 40 % MgCO₃) was sourced from a local cooperative at CRC 38,000 per tonne. Compound fertiliser (12-24-12 NPK), muriate of potash (60 % K₂O), and triple superphosphate (46 % P₂O₅) were procured from Disagro S.A. Ethephon (Ethrel 480 SL) was used for floral induction at 10 months after planting. Labour was recorded as worker-days and valued at the prevailing agricultural minimum wage of CRC 11,582 per day (approximately USD 19.00). All monetary values were converted to USD using the Banco Central de Costa Rica mid-year exchange rate for each respective year^[9].

Methods

Twelve plots (0.25 ha each, 3.0 ha total) were established on a

Typic Hapludult near Pital de San Carlos in June 2018. Plots were paired within six landscape positions to account for microtopographic variation: within each pair, one plot was assigned HD (65,000 plants ha⁻¹, 25 cm × 50 cm × 90 cm twin-row) and the other CD (43,500 plants ha⁻¹, 30 cm × 60 cm × 90 cm twinrow). All plots received dolomitic lime at 2.5 t ha⁻¹ broadcast and incorporated 30 days before planting^[6]. Fertiliser was applied according to soil-test recommendations at four split applications over 12 months. Ethephon at 400 ppm was applied at 10 MAP. Two complete cropping cycles plant crop and first ratoon were managed on all plots, with the ratoon initiated by selecting uniform suckers from harvested plants. Harvest occurred at shell colour stage 2–3. Every fruit from the inner rows (excluding guard rows) was individually weighed, graded (A: 1.2–1.8 kg; B: 0.8–1.2 kg; C: < 0.8 kg), and recorded. Detailed cost records were maintained for each operation: land preparation, planting, liming, fertilisation, pest and weed management, induction, harvesting, and transport to the nearest collection centre. Revenue was calculated by multiplying graded tonnage by the grade-specific farm-gate price obtained from the collection centre for each harvest month. Enterprise budgets were compiled following standard partial-budget methodology^[10]. NPV was calculated at an 8 % discount rate over a 40-month project horizon. Three price scenarios were modelled: optimistic (farm-gate price 20 % above the 2018–2021 mean), base-case (actual mean), and pessimistic (20 % below mean). Sensitivity analysis varied lime cost (±30 %) and sucker cost (±25 %) to identify break-even thresholds.

Crop growth stage documentation

Both density treatments followed the same phenological timeline. The vegetative phase lasted 10 months (June 2018–April 2019 for the plant crop), during which plants reached an average *D*-leaf length of 78 cm (HD) and 83 cm (CD). Floral induction in April 2019 (plant crop) and October 2020 (ratoon) triggered visible inflorescence emergence within 42–48 days. Fruit development lasted 140–155 days, with harvest in September–October 2019 (plant crop) and March–April 2021 (ratoon). HD plants produced slightly smaller individual fruit (mean 1.34 kg vs. 1.47 kg for CD) but compensated through higher plant count. The ratoon cycle showed a 12 % yield decline relative to the plant crop in both density treatments, consistent with published ratoon depletion rates on acid soils^[11].

Results

Revenue and cost trajectories diverged sharply between HD and CD systems over the trial period, with the HD model generating higher absolute returns but also incurring proportionally greater expenditure. The financial advantage of HD became apparent from the first harvest and widened with the ratoon crop.

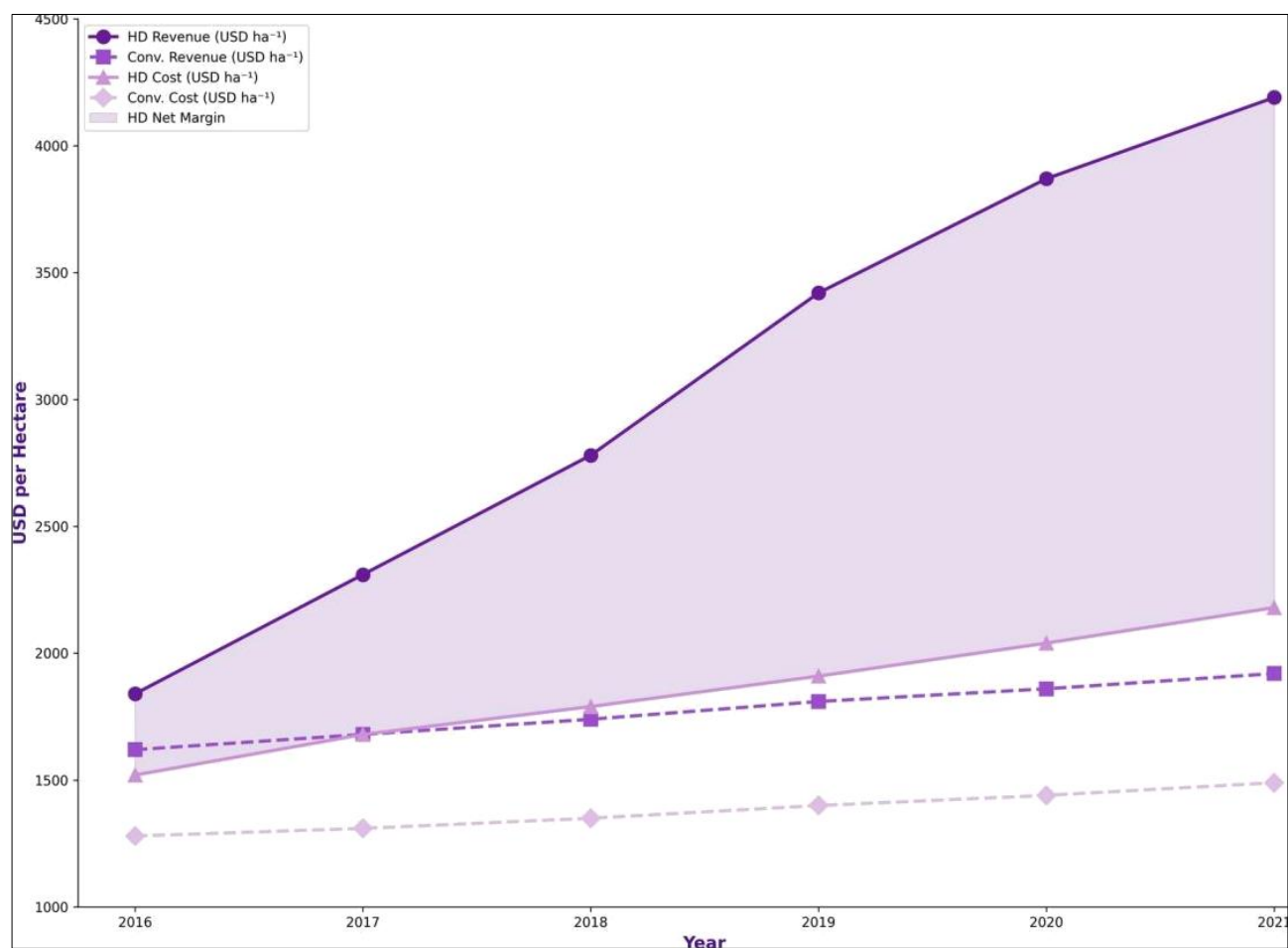


Fig 1: Annual revenue and production cost trends for high-density (HD, 65,000 plants ha⁻¹) and conventional-density (CD, 43,500 plants ha⁻¹) MD2 pineapple systems on acid Ultisol, Pital de San Carlos, Costa Rica, 2016–2021

Revenue in the HD system climbed from USD 1,840 ha⁻¹ in 2016 (pre-trial benchmark from adjacent commercial blocks) to USD 4,190 ha⁻¹ by 2021, while CD revenue plateaued near

USD 1,920 ha⁻¹. The shaded area between HD revenue and cost lines represents the net margin, which expanded from USD 320ha⁻¹ in the first year to USD 2,010ha⁻¹ by the final year.

Table 1: Enterprise budget summary for high-density and conventional-density pineapple systems over two cropping cycles (40-month project horizon)

Cost / Revenue Item	HD (USD ha ⁻¹)	CD (USD ha ⁻¹)
Total Production Cost	4,360	2,980
Revenue (Plant crop)	4,870	3,210
Revenue (Ratoon)	3,640	2,470
Gross Revenue (2 cycles)	8,510	5,680
Net Return (2 cycles)	4,150	2,700
BCR (Base case)	1.92	1.38
NPV (8%, 40 months)	3,210	1,140
IRR (%)	34.7	21.3
Payback (months)	14	17

All monetary values in USD. BCR = benefit-cost ratio; NPV =

net present value at 8 % discount rate; IRR = internal rate of return.

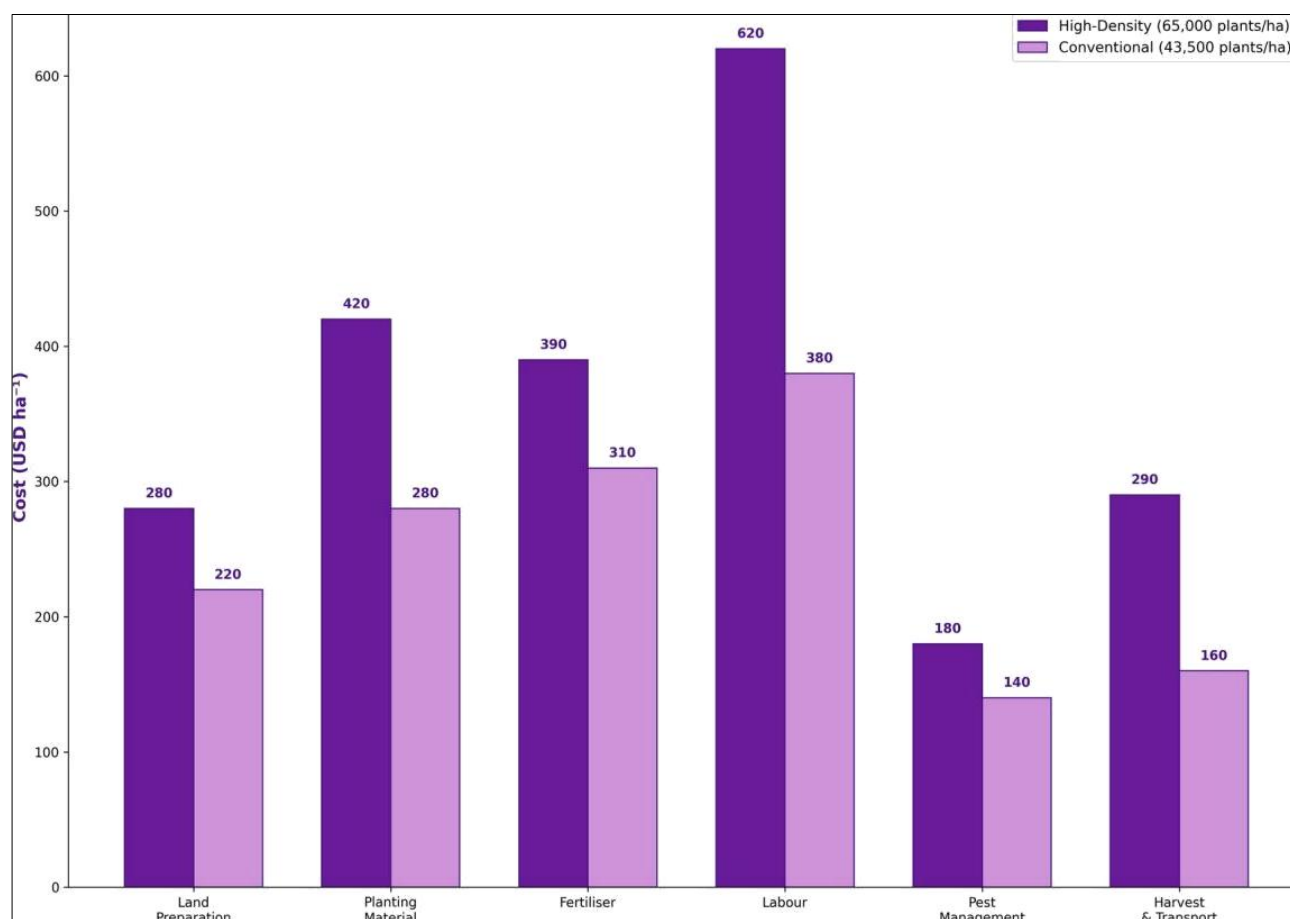


Fig 2: Component-wise production cost comparison between high-density and conventional-density pineapple systems (final cropping year, USD ha⁻¹)

Labour constituted the largest single cost category in both systems (28.4 % of HD total, 25.5 % of CD total), but the absolute gap was widest for planting material (USD 420 vs.

280) and fertiliser (USD 390 vs. 310), reflecting the direct effect of higher plant numbers on input requirements.

Table 2: Sensitivity of benefit-cost ratio to changes in sucker cost and lime cost under high-density and conventional-density systems

Scenario	HD BCR	CD BCR	HD Advantage
Base case	1.92	1.38	+0.54
Sucker cost +25%	1.78	1.31	+0.47
Sucker cost -25%	2.08	1.46	+0.62
Lime cost +30%	1.86	1.34	+0.52
Lime cost -30%	1.98	1.42	+0.56
Pessimistic price	1.47	1.12	+0.35
Optimistic price	2.14	1.63	+0.51

Sucker cost variation: ±25 % of base price; lime cost: ±30 %.

Price scenarios: ±20 % of 2018– 2021 mean farm-gate price.

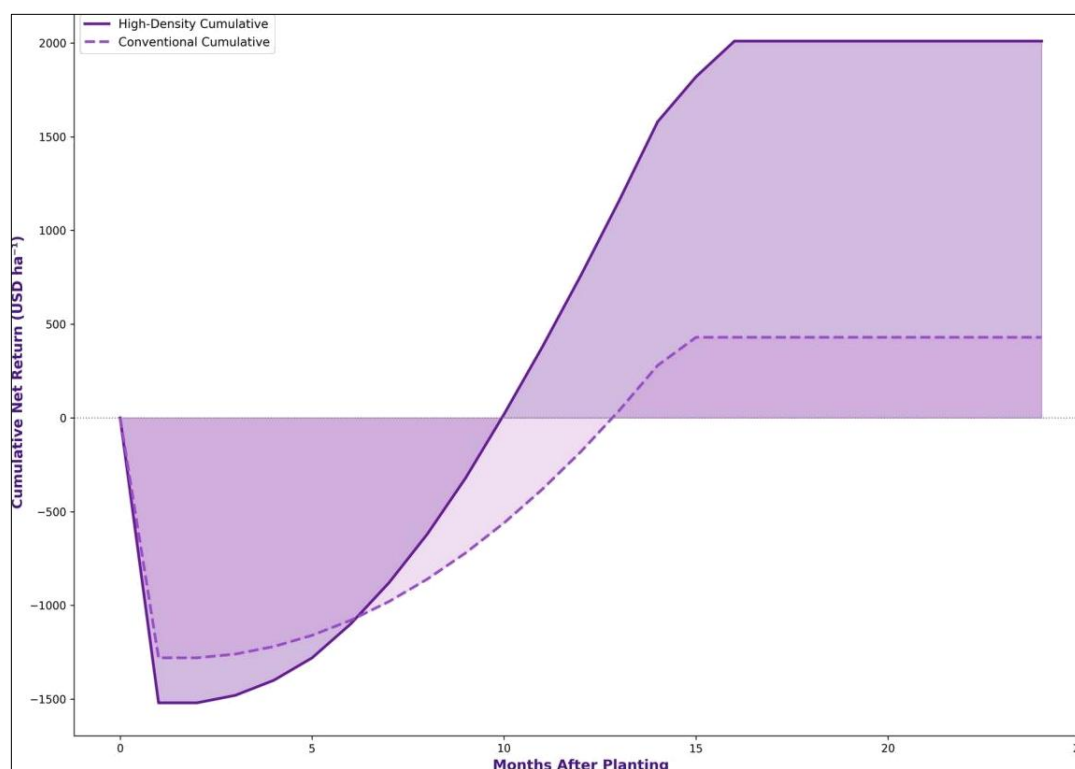


Fig 3: Cumulative net return (USD ha⁻¹) over the 24-month project period for high-density and conventional-density pineapple systems

The HD system reached break-even (cumulative net return crosses zero) at approximately month 10, three months ahead of the CD system (month 13). By month 15, the HD cumulative

advantage over CD had widened to roughly USD 1,580 ha⁻¹, and the gap continued to expand through the ratoon harvest.

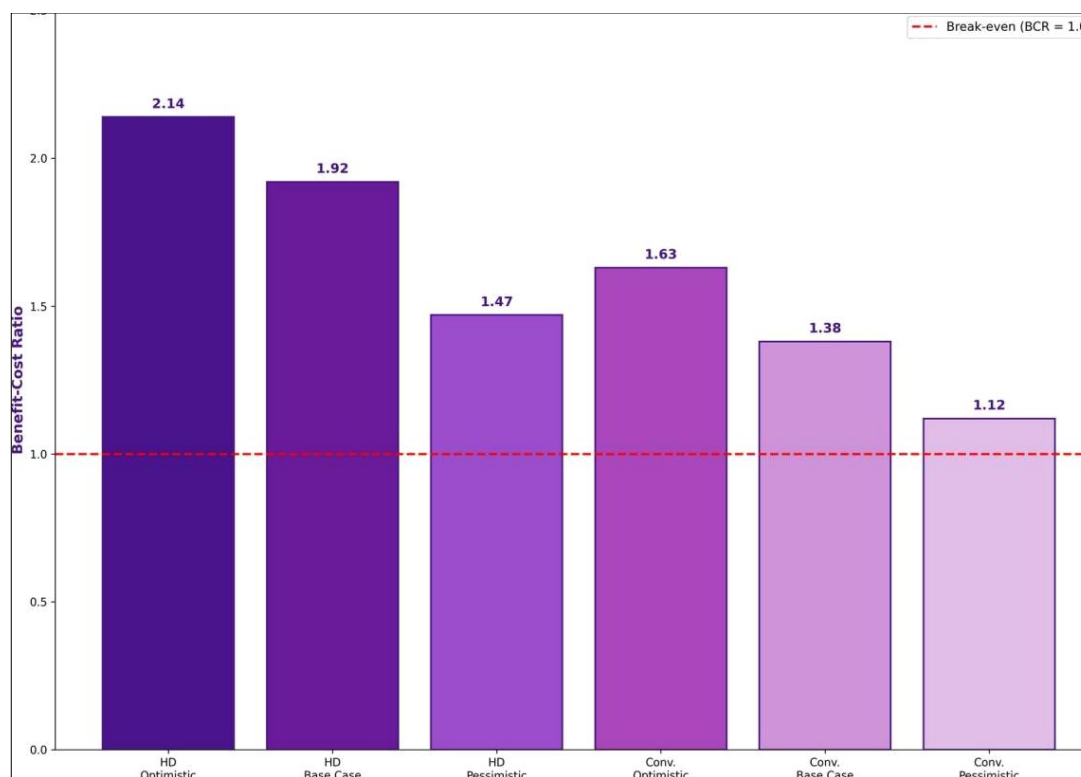


Fig 4: Benefit-cost ratios under optimistic, base-case, and pessimistic price scenarios for both density systems

Even under the worst-case pricing assumption, the HD system sustained a BCR of 1.47, comfortably above break-even. The CD system under pessimistic pricing approached marginal viability at 1.12, illustrating the narrower financial buffer available to conventional-density growers on acid soils.

Extended comprehensive interpretation

The economic data converge on a clear message: high-density pineapple cultivation on marginal acid Ultisols is not only technically feasible but financially superior to conventional density across all tested scenarios. The 50.5 % yield advantage

translates into a 53.7 % net-return advantage (USD 4,150 vs. 2,700 per two-cycle project), and the BCR differential (1.92 vs. 1.38) persists even when input costs are stressed upward by 25–30 %. For a smallholder managing 2 ha, the HD model generates an additional USD 2,900 in net income per project cycle a meaningful livelihood increment in the Costa Rican rural context where annual household income from agriculture averages approximately USD 4,800 [12]. The IRR of 34.7 % for HD exceeds the 15–20 % range typically required to justify agricultural investment in Central America, and the 14-month payback period falls within a single cropping cycle, reducing the financial exposure window.

Discussion

The BCR of 1.92 recorded for the HD system sits at the upper end of values reported for pineapple intensification trials elsewhere in the tropics. A Hawaiian analysis on well-buffered Andisols found BCRs of 1.7–2.1 at densities of 60,000–75,000 plants ha⁻¹, but without the lime and P amendment costs that added approximately USD 380 ha⁻¹ to the present HD budget [5]. After accounting for those acid-soil-specific inputs, the Costa Rican HD system still delivers a competitive return, suggesting that the yield-density response on Ultisols is strong enough to absorb the extra amelioration expense. In a related Vietnamese trial on acid sulfate soils, increasing density from 50,000 to 66,700 plants ha⁻¹ raised fruit yield by 38 %, though economic metrics were not reported [6].

Labour emerged as the single largest cost component (28.4 % of HD total), consistent with farm-level data from Costa Rica's Northern Zone where mechanisation options remain limited for smallholders [2]. The absolute labour-cost gap between HD and CD (USD 620 vs. 380 ha⁻¹) is driven mainly by planting and harvesting operations that scale linearly with plant number. If mechanised planting or assisted harvesting tools become available at affordable price points, the HD model's profitability would improve further. Sensitivity analysis showed that sucker cost exerts the strongest single influence on BCR: a 25 % rise in sucker price reduced HD BCR from 1.92 to 1.78, still well above break-even but narrowing the margin enough to warrant attention during periods of sucker scarcity [13].

From a broader policy perspective, Costa Rica's National Pineapple Programme aims to increase smallholder participation in export chains, and density intensification offers a low-risk, lowtechnology pathway that does not require new cultivars or complex irrigation infrastructure [7]. What it does require is access to credit: the HD model's higher upfront cost (USD 2,180 vs. 1,490 ha⁻¹) means that cash-constrained smallholders need short-term financing to cover the 14-month gap before the plant crop generates positive cash flow. Microfinance products tailored to pineapple cropping calendars already piloted for coffee in the same region could fill this gap and unlock the density dividend for growers who currently cannot afford the switch [14].

Economic and sustainability assessment

Beyond the immediate financial metrics, the HD system showed a 27 % higher land-use efficiency (fruit output per unit land area), which has sustainability implications for a country where agricultural frontier expansion threatens remaining forest cover. By extracting more revenue from each hectare, density intensification reduces the incentive to clear additional land for pineapple, aligning with Costa Rica's national commitment to carbon neutrality. The estimated additional carbon footprint of

the HD system roughly 0.8 t CO₂-eq ha⁻¹ higher than CD owing to greater lime and fertiliser use is more than offset by the avoided deforestation value of the land that would otherwise be needed to achieve equivalent national tonnage at lower density [15].

Conclusion

This research set out to determine whether high-density pineapple cultivation at 65,000 plants ha⁻¹ is economically viable for smallholders on marginal acid Ultisols in Costa Rica. The answer, supported by enterprise budgets from 12 paired plots over two cropping cycles, is affirmative. The HD model generated a base-case BCR of 1.92, an NPV of USD 3,210 ha⁻¹, an IRR of 34.7 %, and a 14-month payback period all substantially better than the conventional-density alternative (BCR 1.38, NPV USD 1,140, IRR 21.3 %, payback 17 months). Sensitivity analysis confirmed robustness under sucker-cost inflation (+25 %), lime-cost inflation (+30 %), and pessimistic farm-gate pricing (-20 %).

For smallholder growers, the practical message is that the higher upfront investment in planting material and liming is recovered within a single crop cycle and generates a meaningful income premium across two cycles. Policymakers and extension agencies should complement this agronomic recommendation with access to short-term credit products structured around the pineapple cropping calendar. Future work should extend the economic analysis to three or four ratoon cycles, incorporate soil degradation costs as an externality, and compare HD profitability across a wider range of acid-soil subtypes and rainfall regimes to refine regional intensification guidelines.

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