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Abstract

Diversification of beekeeping through pollen and bee venom harvesting is increasingly promoted as a strategy for improving smallholder incomes. However, empirical evidence on its economic implications in Sub-Saharan Africa remains limited. This study assessed production and incremental financial performance of pollen and bee venom harvesting technologies from 18 identical top-bar hives in Singida Region, Tanzania. The hives comprised equally distributed untrapped (control), pollen and venom-trapped hives assessed during high and low harvesting seasons in 2024. Measured yields were combined with equipment purchase costs, operating-cost schedules and January 2025 market prices. Honey yield was analysed by repeated-measures ANOVA with district blocking; financial performance was evaluated using matched incremental budgets and a five-year appraisal at a 10% discount rate. Honey yield significantly differed among technologies and harvest seasons, with no significant interaction of technology and season. Holm-adjusted *p*-values indicated that, the averaged across harvests, untrapped hives yielded significantly more honey than pollen and bee-venom trapped hives, while bee venom trapped hives yielded significant more honey than pollen-trapped hives. Pollen and bee venom production was significantly higher in high season than in the low harvesting season. Estimated gross revenue was significantly higher in venom trapped hives. Venom harvesting generated larger absolute benefits, while pollen harvesting required less capital and achieved higher proportional returns. These conditional appraisal results support diversification under the stated assumptions; larger, multi-year studies with verified sales are required to establish long-term performance.

Keywords: bee products; experimental yield; incremental budget; investment appraisal; pollen trap; venom collector

Introduction

Beekeeping supports rural livelihoods, food systems and ecosystem services, while honey and other bee products supply expanding food, cosmetic and pharmaceutical markets. Bee products hold significant value in international trade, largely due to their nutritional and medicinal properties. Of these, honey remains the dominant product, with global production expanding from 577,000 tons in 1961 to more than 1.8 million tons by 2021 (Popescu et al. 2023). China accounts for the largest share of this production (25.81%) (Puranik, et al. 2023), while Canada leads globally in hive productivity (Bixby et al. 2020; Mohan et al. 2023). The global honey market in 2020 was valued at USD 9.21 billion and is projected to grow annually by 8.2%, driven by rising demand for natural and health-enhancing products (Mohan et al. 2023; Puranik, et al. 2023). Currently, China is the world's top honey exporter with shipments valued at USD 254,227,170.00 (152,636,000 kg), followed by New Zealand and Argentina at comparatively lower volumes and values (World Integrated Trade Solution 2023). Overall, the expansion of global honey production and trade underscores beekeeping's critical role in sustaining livelihoods, enhancing food security, and driving environmentally aligned economic growth, with the potential to explore other related products.

Bee pollen and venom have established themselves as valuable bee products in international markets (Boyacioglu et al. 2022). The global bee pollen market was valued at USD 833.9 million in 2023 and is projected to reach USD 1.25 billion by 2030, growing at a compound annual growth rate of 6.1% (Grand View Research 2025). Bee venom also commands significant market value, with an estimated global market size of USD 327.5 million in 2022 and a projected increase to USD 540 million by 2032 (Sable et al. 2024). This increase in market size is attributed to the fast annual growth rate in the productivity of bee products (European Commission 2024). The rapid expansion of global honey, pollen, and bee venom markets, reflected in their substantial annual growth rates, highlights their potential to enhance beekeepers' livelihoods and contribute to broader bio-economy development.

Pollen and bee venom offer a valuable global pathway to enhance beekeepers' income, productivity, profitability and market advantage (Schouten 2021a; Ferreira et al. 2023); despite their tendency to reduce honey yields (Hoover and Ovinge 2018; Carpena et al. 2020; De Graaf et al. 2021). Pollen and bee venom harvesting technologies diversify revenue streams and compensate for potential losses in honey production, reinforcing their significance in enhancing the overall economic viability of beekeeping (Puranik, et al. 2023; Chen et al. 2023). Thus, their inclusion in beekeeping holds strong potential to significantly increase profit margin and net farm income with minimal increase in cost

across beekeeping enterprises (Nwaihu 2015). In general, despite modest reductions in honey yield, the integration of pollen and bee venom harvesting diversifies beekeeping productivity, strengthens economic viability, enhances profitability, and improves overall net farm returns with relatively limited additional costs.

The profitability and viability analysis for the beekeeping enterprises is determined using production cost (variable and fixed costs) and associated returns (George 2025). Thus, the revenue and profitability performance derived from cost and returns enhances the computation of revenue and profitability performance, including the gross margin (GM), used to compute returns from different hive products (Kiprono et al. 2024). Other profitability and viability indicators such as net income (NI), benefit-cost ratio (BCR), cost structure, return on investment, and break-even point (Ladino et al. 2023). These indicators provide robust tools to understand the financial and economic transformation achieved through honey, pollen and venom harvesting (Abdurofi et al. 2021; Feketéné Ferenczi et al. 2023; Rahmad et al. 2024). Overall, integrating honey, pollen, and venom harvesting enhances profitability and sustainability by generating high-value products that strengthen beekeepers' incomes and livelihoods.

Beekeeping is a significant economic activity in Tanzania, engaging over two million individuals in both rural and urban areas (MNRT 2021). Honey and beeswax remain the primary products from beekeeping in Tanzania. However, global markets show rapid growth in honey, pollen, and bee venom products (Boyacioglu et al. 2022). Accordingly, pollen and bee venom harvesting have emerged as new technologies in various regions in Tanzania (TAFORI 2020). Previously, it was substantiated that the value chains for pollen and bee venom were not developed and were nearly non-existent in local markets in Tanzania (USAID 2009). Despite growing evidence on the profitability of pollen and venom globally, little is known about their profitability, financial performance and overall contribution to beekeepers' economic benefits. This knowledge gap limits their contribution to enhancing livelihoods and strengthening the economic viability of beekeeping.

This study therefore used experimentally observed honey, pollen and bee venom yields to evaluate the annual gross revenue and incremental financial performance of pollen and venom harvesting technologies relative to untrapped hives. The analysis was designed to answer three questions: whether hive technology and harvest period affected honey yield; how much additional pollen or venom was recovered per hive; and whether the value of those products compensated for foregone honey, additional operating expenditure and technology-specific capital.

Materials and methods

Description of study area

The study was conducted in Singida Region, lying between latitudes 3° 52'S and 7° 34'S, and longitudes 33° 27'E and 35° 26'E (Figure. 1). Six Districts namely; Ikungi, Itigi, Iramba, Manyoni, Singida District Council and Singida Municipal Council were involved in this study (Figure. 1). Singida Region produces 50% of the honey and beeswax produced in Tanzania, and Manyoni is the leading district in the productivity of bee products (URT 2020). Moreover, Singida Region has been growing in its adoption of modern technology. For example, the use of modern beehives increased from 9,695 in 2010 to 17,699 in 2015 (URT 2017). Moreover, Singida has a total of 145 beekeeping enterprises, of which 11 are registered as cooperatives (URT 2024). The region forms part of the semi-arid part of Central Tanzania, experiencing low rainfall in a short rainy season which are often erratic. The short rain season extends between December and March; and the long dry season from April to November (URT 2020).

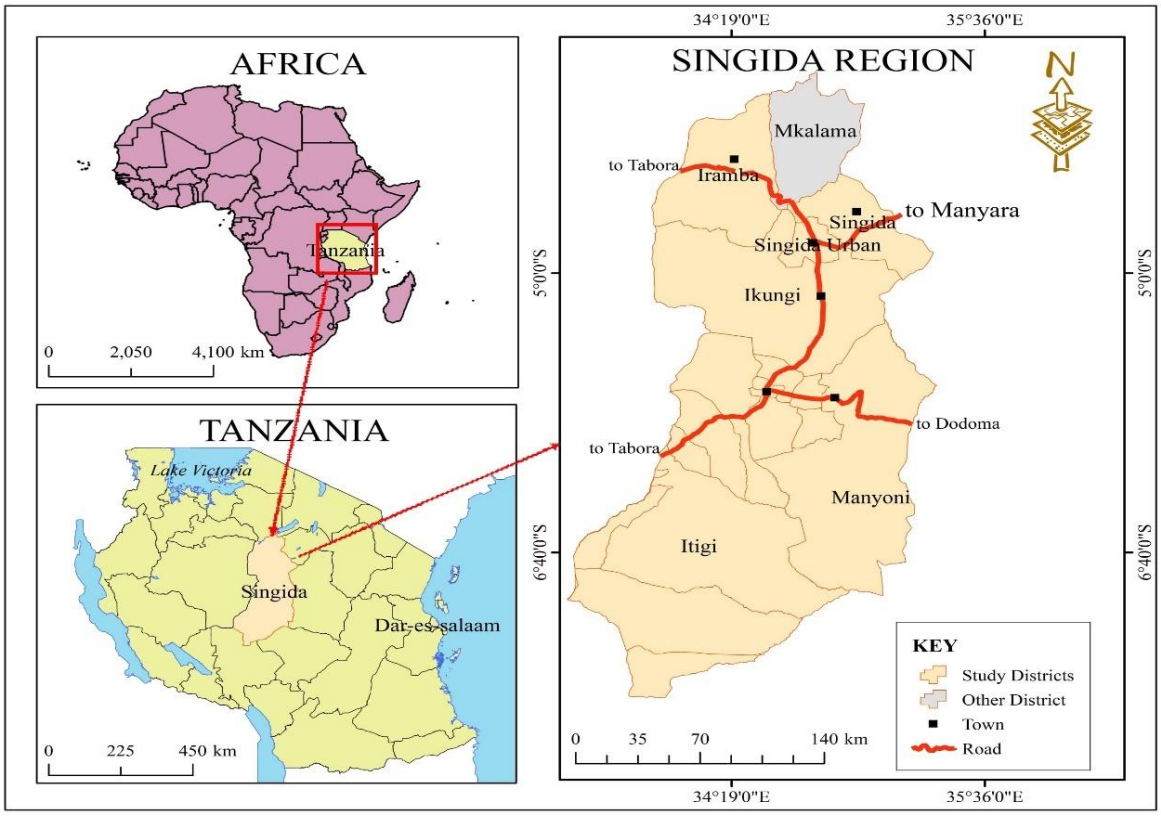

Fig. 1 Location of the six experimental districts in Singida Region, Tanzania.

Study design and experimental units

A repeated measures field study was conducted at six experimental sites, one in each study district, using 18 identical top-bar hives. At each site, one untrapped hive (control), one pollen-trapped hive, and one bee-venom-trapped hive were monitored, providing six hives per technology comparable to sample sizes used in previous field-based apicultural studies (Muruke 2014a; Muruke 2014b). The use of identical hive designs supported comparability among technologies. The study targeted beekeepers practicing both pollen and bee venom harvesting under comparable field conditions. Thus, the hives, pollen and bee venom traps were owned and managed by beekeepers from the study area. The study ensured that the devices were from the same manufacturer to ensure comparability of equipment. The same district-technology hive units were measured in two harvests: the low (wet) season on 25th January 2024 and the high (dry) season on 2nd September 2024. These harvests represented accumulation windows of 86 and 221 days, respectively. Honey was harvested using standard apicultural practice by using smokers to remove bees from honeycombs and carefully extracting honey. During each harvest, capped combs were weighed before and after extraction, and the difference was verified using a calibrated digital balance. Honey was weighed separately for each experimental hive at each harvest period. Net honey yield was recorded in kilograms per hive. The sampling strategy was designed to balance experimental control with field-level representativeness. Pollen was collected using traps fitted at hive entrances, which dislodged pollen pellets from the hind legs of returning foragers into collection trays. Bee venom was harvested using electrical venom collectors, which stimulated bees to sting a collection surface. The deposited venom was allowed to dry before being carefully scraped off and collected. Pollen was measured in kilograms from pollen-trapped hives, while bee venom was measured in grams and divided by 1,000 to convert in kilograms from venom-trapped hives. This conversion was applied before every revenue and investment calculation. Annual production per hive was aggregated by summing the two observed harvests.

Price and cost data

The experiment supplied the production quantities used in the economic analysis. Cost estimates were based on the purchase prices of items procured during the study, while product prices were obtained through a survey of beekeeping markets and enterprises. All costs are presented as equivalent to thousands of USD, at the exchange rate of 1 USD equal to Tanzanian shillings (TZS) 2,645 as at 15th January 2025. Results are presented primarily in TZS. Because the price date follows the 2024 harvest, the estimates represent an ex-post budget at constant January 2025 prices rather than cash actually received during harvest. Annual variable operating costs and initial fixed-asset investments were

compiled separately for each hive system. Honey containers were classified as variable costs and included consistently because all three systems produced honey. Recorded zero charges were retained as zero. Incremental operating cost was calculated as the diversified-system cost minus the matched untrapped-system cost. Common fixed assets were valued consistently from the untrapped reference and cancelled in the incremental comparison. Six pollen traps and six venom-collection machines were purchased, corresponding to one specialised device per treated hive; a separate weighing scale was also assigned to each treated hive. The resulting cost structure is reported in Table 3. Initial fixed-asset expenditure was distinguished from annual operating expenditure and was not charged again as an annual cost.

Economic analysis and assumptions

The economic analysis used a matched incremental partial budget. For each district block *i*, the diversified technology *k* was compared with the untrapped control, denoted by 0. Products were indexed by *j*, and appraisal years by *t*. This approach estimated the financial consequence of adopting pollen or bee venom harvesting while preserving the experimental district matching (Djokoto and Zigah 2021).

Annual gross revenue. Gross revenue for technology *k* in district *i* was calculated as the sum of the value of all products harvested (honey, pollen and bee venom) during the two periods. The annual gross revenue was computed as;

$$GR_{ik} = \sum_{j=1}^{j} P_j Q_{jik}$$

whereas GR_{ik} = annual gross revenue per hive, P_j = the constant price of product *j*, Q_{jik} = the annual quantity of product *j*, and *J* = the number of products generated by the technology. Honey and pollen quantities were expressed in kilograms.

Incremental gross revenue. The additional gross revenue attributable to a diversified technology was calculated against the matched untrapped hive in the same district. A positive value indicates that the additional product revenue exceeded the value of any honey foregone before additional operating cost was considered. The Incremental gross revenue was calculated as follows;

$$\Delta GR_{ik} = GR_{ik} - GR_{i0}$$

whereas ΔGR_{ik} = the change in gross revenue from adopting technology *k*, GR_{ik} is gross revenue from the pollen or venom trapped hive, and GR_{i0} = gross revenue from the untrapped control.

Annual incremental net benefit. Additional operating cost was then deducted from incremental gross revenue. A negative value denotes a recorded cost saving rather than an additional cost. The annual incremental net benefit was computed as;

$$INB_{ik} = \Delta GR_{ik} - AOC_k$$

$$\overline{INB_k} = \frac{1}{B}\sum_{i=1}^{B} INB_{ik}$$

where INB_{ik} = annual incremental net benefit for district i, AOC_k = the stated additional annual operating cost of technology k, $\overline{INB_k}$ = the mean annual incremental net benefit, and B = 6 district blocks.

Technology-specific capital allocation. Pollen and bee venom trap devices were the technology specific capital allocation owned by beekeepers. Participating beekeepers reported the purchase costs of these traps, which were classified as technology-specific fixed costs. Thus, six pollen and venom-harvesting machines were used in for the six pollen and venom-treated hives. The cost of a weighing scale was recorded for each treated hive. No machine-sharing allocation or alternative hive-service scenario was applied. Beehives, protective gear, smokers, hive tools, brushes, headlamps, honey gate valves, strainers, hanging materials, queen catchers and hive stands were valued consistently across systems and cancelled in the incremental budget.

$$K_{k,h} = K_k$$

where $K_{k,h}$ = is technology specific capital assigned to one treated hive, K_k = is the purchase cost of the specialised device for that hive, and H_k = the number of hives serviced by that asset.

Net present value. The five-year NPV was calculated from the mean annual incremental net benefit and the technology-specific capital assigned to each treated hive.

$$NPV_k = -K_{k,h} + \sum_{t=1}^{n} \frac{\overline{INB_{kt}}}{(1+r)^t}$$

where NPV_k = the net present value, $K_{k,h}$ = initial capital per hive at year 0, INB_{kt}= mean incremental net benefit in year t, r = the discount rate and n = the appraisal period. The base appraisal used r = 0.10 and n = 5. Yields, real prices and real operating costs were assumed constant, cash flows occurred at year-end, salvage value was zero, and taxes, financing charges and inflation were excluded.

Internal rate of return (IRR). IRR was defined as the discount rate that reduced NPV to zero. An IRR was reported only when the cash-flow sequence produced a valid positive root. It was therefore calculated for pollen harvesting but not for venom harvesting, whose annual incremental net benefit remained negative.

$$0 = -K_{k,h} + \sum_{t=1}^{n} \frac{\overline{INB_{kt}}}{(1+IRR)^t}$$

where IRR = Internal rate of return, $K_{k,h}$ = initial capital per hive at year 0, INB_{kt}= mean incremental net benefit in year *t*, *r* = the discount rate and *n* = the appraisal period

Profitability index. The profitability index measured the present value of future incremental net benefits per unit of initial technology-specific capital. A profitability index greater than 1 indicates that discounted incremental benefits exceed initial capital. The index was interpreted only for a technology with positive future incremental net benefits. The profitability index was calculated as;

$$PI_k = \frac{\sum_{t=1}^{n} \frac{\overline{INB}_{kt}}{(1+r)^t}}{K_{k,h}}$$

where PI_k = profitability index, $K_{k,h}$ = initial capital per hive at year 0, $\overline{INB}_{kt}$= mean incremental net benefit in year *t, r* = the discount rate and *n* = the appraisal period.

Payback period. The simple payback period was calculated as:

$$PP_k = \frac{K_{k,h}}{\overline{INB_k}}$$

where PP_k = the number of years required for undiscounted incremental net benefits to recover initial capital, $K_{k,h}$ = initial capital per hive at year 0, INB_{kt}= mean incremental net benefit in year *t.* The equation is meaningful only when $\overline{INB}_k > 0$; therefore, it was not reported for venom harvesting.

Discounted break-even product price. The break-even price was defined as the price of the additional product that makes the five-year NPV equal to zero. First, the present-value annuity factor was calculated as:

$$A_{r,n} = \sum_{t=1}^{n} \frac{1}{(1+r)^t}$$

$$P^*_{D,k} = \frac{P_H(Q_{H,0} - Q_{H,k}) + AOC_k + K_{k,h}/A_{r,n}}{Q_{D,k}}$$

where $P^*_{D,k}$ = the discounted break-even price of the additional product, P_H = the honey price, $Q_{H,0} - Q_{H,k}$ = honey foregone relative to the untrapped control, AOC_k= $OC_k - OC_0$ is the incremental operating cost difference, $Q_{D,k}$ = annual pollen or venom output, and $A_{r,n}$ converts initial capital into an equivalent annual capital recovery amount. For venom, $Q_{D,k}$ was entered in kilograms after conversion from grams. This equation assumes one additional product, constant annual quantities and costs, and a zero NPV criterion.

Five-year cumulative return on investment (ROI). ROI was calculated as a five-year cumulative percentage from undiscounted cumulative incremental net benefits after recovery of initial technology-specific capital. The discounted ROI was not reported separately.

$$ROI(\%) = [(\Sigma INB_t - I_0)/I_0] \times 100 = \left[\frac{5 \times \overline{INB} - I_0}{I_0}\right] \times 100$$

where $INB_t =$ the annual incremental net benefit, and $I_0 =$ initial initial additional capital, and NPV = net present value

Discounted incremental benefit–cost ratio (BCR). Benefits comprised additional-product revenue plus any operating-cost savings**.** Costs comprised foregone honey revenue, any additional operating expenditure and initial technology-specific capital. Positive and negative operating-cost (OC) differences were allocated to costs and benefits respectively, without double counting. Both streams were discounted at 10% over five years; common costs were cancelled (Shively 2012). Depreciation was not added to the cash-flow costs because initial capital was already included.

$$BCR = [\Sigma\, B_t/(1+r)^t]/\left[I_0 + \frac{\Sigma C_t}{(1+r)^t}\right] for\ t = 1, \ldots, 5$$

where B_t = additional-product revenue plus maximum (−ΔOC, 0), C_t = foregone honey revenue plus maximum (ΔOC, 0), and ΔOC = operating cost of the diversified system minus that of the untrapped system.

Statistical analysis

All data obtained were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test. Honey yield was analysed by repeated-measures ANOVA with technology, period and their interaction as fixed effects. The F-tests for technology, harvest period and their interaction used the district-by-technology, district-by-season and district-by-technology-by-season interactions, respectively, as error terms. Partial eta squared was computed using the relevant effect and error sums of squares. Technology comparisons used paired district contrasts of per-hive means across harvests, with Holm-adjusted p-values and unadjusted 95% confidence intervals. Pollen and bee-venom were analysed separately using paired-samples *t*-tests of high-minus-low harvest season differences across six sites. Annual output was summed within hives before valuation. All product quantities and unit prices were expressed per kilogram. Annual gross revenue was analysed using complete-block ANOVA followed by paired district contrasts with Holm adjustment. Statistical analyses were performed using Python (version 3.12.14), with NumPy (version 2.3.5) for numerical calculations and SciPy (version 1.17.0) for statistical testing and numerical optimisation. The results are

presented as mean ± standard deviation across six sites. Statistical significance was set at $p < 0.05$, with emphasis on effect sizes and confidence intervals because only six blocks were available

Results

Honey, pollen and bee-venom production

Annual honey production averaged 21.50, 17.83 and 19.67 kg per hive for untrapped, pollen-trapped and venom-trapped hives, respectively (Table 1). Averaged across harvests, untrapped hives yielded 1.83 kg more honey than pollen-trapped hives (Holm-adjusted $p = 0.00245$) and 0.92 kg more than venom-trapped hives ($p = 0.04783$); venom-trapped hives yielded 0.92 kg more than pollen-trapped hives ($p = 0.02421$). Annual pollen and venom output averaged 5.25 ± 1.29 kg and 1.02 ± 0.30 kg per treated hive. High-minus-low harvest increases averaged 0.917 kg for pollen ($t = 3.84$; $p = 0.012$) and 0.217 kg for venom ($t = 13.00$; $p < 0.001$).

Table 1 Experimental product yields per hive across six district blocks

Technology	Product	Low season mean ± SD	High season (mean ± SD)	Annual (mean ± SD)
Untrapped	Honey (kg)	7.58 ± 1.96	13.92 ± 2.69	21.50 ± 4.43
Pollen trapped	Honey (kg)	6.50 ± 2.07	11.33 ± 1.97	17.83 ± 3.43
Venom trapped	Honey (kg)	6.92 ± 1.86	12.75 ± 2.30	19.67 ± 3.72
Pollen trapped	Pollen (kg)	2.17 ± 0.68	3.08 ± 0.74	5.25 ± 1.29
Venom trapped	Bee venom (kg)	0.40 ± 0.14	0.62 ± 0.16	1.02 ± 0.30

The repeated-measures blocked ANOVA showed honey yield differed significantly among hive technologies ($F = 20.51$, $p < 0.001$, partial $\eta^2 = 0.804$) and between harvest seasons ($F = 74.74$, $p < 0.001$, partial $\eta^2 = 0.937$), with higher yields recorded during the later harvest period (Table 2). Both effects had large partial effect sizes. The interaction of technology by the harvesting season was not statistically significant ($F = 2.36$, $p = 0.145$, partial $\eta^2 = 0.321$), indicating that the ranking was broadly similar in both harvest seasons.

Table 2 Repeated-measures randomized complete-block ANOVA for honey yield

Effect	df numerator	df denominator	F	p	Partial η^2
Technology	2	10	20.51	<0.001	0.804
Harvest period	1	5	74.74	<0.001	0.937
Technology and season interaction	2	10	2.36	0.145	0.321

Cost structure of the alternative hive technologies

The annual variable cost was TZS 300,000 per untrapped hive, TZS 245,000 per pollen-trapped hive and TZS 300,000 per venom-trapped hive (Table 3a). Packaging recorded the largest operating item, accounting for 31.7%, 34.7% and 28.3% of the respective hive technology totals. Harvesting and handling labour accounted for a further 20.0%, 24.5% and 20.0%, respectively. Pollen harvesting had TZS 55,000 lower annual operating costs than the untrapped system: TZS 10,000 less for packaging, TZS 15,000 less for cleaning and sanitation, and TZS 30,000 less for transport. For venom harvesting, these same reductions were offset by TZS 40,000 for electricity and TZS 15,000 in additional repairs, leaving no net operating-cost difference. Initial fixed-asset investment was TZS 505,500 for an untrapped hive, TZS 565,500 for a pollen-trapped hive and TZS 1,770,500 for a venom-trapped hive under the stated per-hive allocation (Table 3b). Common assets accounted for TZS 505,500 in each system. Additional investment was therefore TZS 60,000 for pollen harvesting, comprising a TZS 45,000 trap and a TZS 15,000 scale, and TZS 1,265,000 for venom harvesting, comprising a TZS 1,250,000 collector and a TZS 15,000 scale. Protective gear accounted for the largest fixed-investment share in the untrapped and pollen-trapped systems (34.6% and 30.9%, respectively), whereas the venom collector accounted for 70.6% in the venom-trapped system. Additional technology-specific capital represented 10.6% of total fixed investment for pollen harvesting and 71.4% for venom harvesting. Only these additional investments entered the incremental financial appraisal because the common assets were identical across systems.

Table 3 Annual variable operating costs and initial fixed-asset investment by hive system, expressed as TZS per hive and percentage of total fixed investment

Cost category	Cost item/Asset	Untrapped		Pollen trapped		Venom trapped	
		Amount	(%)	Amount	(%)	Amount	(%)
(a)Variable costs	Harvesting and handling labour	60,000	20	60,000	24.5	60,000	20
	Protective-material replacement	15,000	5	15,000	6.1	15,000	5
	Electricity (power)	-	-	-	-	40,000	10

	Packaging, including honey containers	95,000	31.7	85,000	34.5	85,000	28
	Cleaning and sanitation materials	20,000	6.7	5,000	2	5,000	2
	Transport to apiary and market	30,000	10	-	-	-	-
	Supplementary colony feeding	30,000	10	30,000	12.2	30,000	10
	Colony health management	10,000	3.3	10,000	4.1	10,000	3
	Harvesting consumables	10,000	3.3	10,000	4.1	10,000	3
	Storage costs	10,000	3.3	10,000	4.1	10,000	3
	Marketing and communication	10,000	3.3	10,000	4.1	10,000	3
	Minor repairs and replacement parts	10,000	3.3	10,000	4.1	25,000	8
	Total annual variable cost	**300,000**	**100**	**245,000**	**100**	**300,000**	100
(b) Fixed costs	Beehives	100,000	19.8	100,000	17.7	100,000	1
	Protective gear	175,000	34.6	175,000	30.9	175,000	10
	Bee smoker	50,000	9.9	50,000	8.8	50,000	3
	Hive tool	15,000	3	15,000	2.7	15,000	1
	Bee brush	12,000	2.4	12,000	2.1	12,000	1
	Bee venom collection machine	-	-	-	-	1,250,000	71
	Headlight	30,000	5.9	30,000	5.3	30,000	2
	Honey gate valve	20,000	4	20,000	3.5	20,000	1
	Honey warmer	-	-	-	-	-	
	Pollen trap	-	-	45,000	8	-	
	Queen catcher	5,000	1	5,000	0.9	5,000	0
	Sieves and strainer	55,000	10.9	55,000	9.7	55,000	3
	Hive suspension wire	3,500	0.7	3,500	0.6	3,500	0
	Rope for hanging beehives	25,000	4.9	25,000	4.4	25,000	1
	Weighing scale for pollen or venom	-		15,000	2.7	15,000	1
	Hive stand	15,000	3	15,000	2.7	15,000	1
	Total initial fixed-asset investment	**505,500**	**100**	**565,500**	**100**	**1,770,500**	**100**
	Additional capital relative to untrapped	0		60,000		1,265,000	

Gross revenue from observed yields

Annual gross revenue averaged TZS 228,607 ± 47,074 per untrapped hive, TZS 636,757 ± 127,623 per pollen-trapped hive and TZS 2,373,691 ± 637,235 per venom-trapped hive (Table 4). Pollen contributed approximately 70% of gross revenue in the pollen-trapped system. Bee venom accounted for approximately 91.2% of total revenue in the venom-trapped hive system. The blocked ANOVA indicated a technology effect on gross revenue ($F = 63.49$, $p < 0.001$, partial $\eta^2 = 0.927$). Pollen-trapped hives generated TZS 408,150 more annual gross revenue than matched untrapped hives (Holm-adjusted $p = 0.00051$). Venom-trapped hives generated TZS 2,145,084 more than untrapped hives (Holm adjusted $p = 0.00077$) and TZS 1,736,934 more than pollen-trapped hives (Holm adjusted $p = 0.00077$).

Table 4 Annual gross revenue per hive calculated from experimental production and constant April 2026 prices

Technology	Honey revenue TZS	Additional product revenue TZS	Total gross revenue TZS mean ± SD	Revenue composition		F	P-value	partial η^2
				Honey (%)	Additional product (%)			
Untrapped	228607	0	228607 ± 47074	100	0	63.49	< 0.001	0.927
Pollen trapped	189620	447137	636757 ± 129035	30	70			
Venom trapped	209114	2,164,578	2,373,691 ± 637,235	8.8	91.2			

Incremental profitability and financial feasibility

Pollen harvesting

Pollen harvesting generated an annual incremental net benefit of TZS 463,150 ± 99,863 (mean ± SD) per hive, including the recorded TZS 55,000 annual operating-cost saving relative to untrapped hives. Additional capital was TZS 60,000 per hive. Five-year NPV at 10% was TZS 1,695,703, IRR was 771.9%, profitability index was 29.26 and the simple payback ratio was 0.13 years. Discounted incremental BCR was 9.16 and five-year cumulative undiscounted ROI was 3,759.6%. The calculated discounted break-even pollen price was non-positive (-35 TZS kg^{-1}). The calculated discounted break-even pollen price was −TZS 35.21/kg; operationally, the threshold is zero under the recorded cost assumptions. This indicates that the recorded operating-cost saving and product mix recovered the specialised capital and foregone honey even at a zero-pollen price.

Bee-venom harvesting

Venom harvesting generated an annual incremental net benefit of TZS 2,145,084 ± 623,690 (mean ± SD) per hive. Annual operating costs were TZS 300,000 in both the venom and untrapped systems, so incremental net benefit equaled incremental gross revenue. Additional capital was TZS 1,265,000 per treated hive. Five-year NPV at 10% was TZS 6,866,556, IRR was 168.4%, profitability index was 6.43 and the simple payback ratio was 0.59 years. Discounted incremental BCR was 6.13 and five-year cumulative undiscounted ROI was 747.9%. The discounted break-even venom price was TZS 347,407/kg, compared with the January 2026 valuation price of TZS 2,129,092.75/kg.

Table 5: Incremental financial performance relative to matched untrapped hives.

Indicator	Untrapped hive (reference)	Pollen harvesting	Venom harvesting
Incremental gross revenue (TZS/hive/year)	0	408,150	2,145,084
Incremental operating cost (TZS/hive/year)	0	−55,000	0
Incremental net benefit (TZS/hive/year)	0	463,150	2,145,084
Technology-specific capital (TZS/hive)	0	60,000	1,265,000
Five-year NPV at 10% (TZS/hive)	0	1,695,703	6,866,556
Five-year discounted BCR at 10%		9.16	6.13
IRR	-	771.90%	168.40%
Five-year discounted ROI undiscounted	-	3759.6%	747.9%
Simple payback ratio (years)	-	0.13	0.59
Discounted break-even product price (TZS/kg)	-	Non-positive (−35)	347,407
Profitability index	-	29.26	6.43

Discussion

The experimental production and recorded cost data indicate positive incremental financial returns from both pollen and bee venom harvesting under the stated valuation and investment assumptions. Although both diversified systems produced less honey than untrapped hives, the value of the additional products compensated for reduced honey and specialised capital. Venom harvesting generated larger absolute net benefit and NPV, whereas pollen harvesting required substantially less capital and achieved higher proportional returns. This distinction is important when comparing income generation with capital affordability (Nwaihu 2015; Ferreira et al. 2023). Thus, profitability was driven not by recovery of honey quantity, but by price differentials and product diversification effects (Puranik, et al. 2023; Chen et al. 2023). In this study, pollen and bee venom commanded prices several-fold higher than honey.

Consequently, despite lower production volumes, the high unit price of pollen and bee venom translated the small harvest quantities into economically significant marginal returns. This underscores the importance of value-based diversification, where integrating high value products such as pollen and bee venom can offset reductions in honey yield and enhance overall economic returns.

Cost structure analysis further revealed that capital investments dominate beekeeping expenditures, with fixed costs accounting for the largest share of total production costs. Fixed costs were principally driven by investment in additional technology-specific capital through the purchase pollen and bee-venom traps. The predominance of fixed costs suggests that diversification into pollen and bee venom harvesting is characterised by high initial capital outlays, which may influence adoption decisions and financial risk exposure. The variable costs were comparatively low, indicating that once initial investments are made, daily beekeeping activities require minimal recurrent expenditure across all technologies (Adjare 1990). However, labour and protective gear emerged as the main contributors to the variable costs, reflecting the increased handling, hive manipulation, and safety requirements associated with pollen and venom harvesting. This finding aligns with evidence from other developing-country beekeeping systems, where labour and safety equipment costs increase as production intensifies or diversifies (Schouten 2021). In this study, the higher fixed cost and comparatively lower variable costs suggest that technology adoption decisions among beekeepers are likely constrained more by up-front investment requirements than by recurrent operating costs.

Both technologies generated positive incremental NPV and discounted incremental BCR above one under the stated assumptions. Venom harvesting produced larger absolute incremental net benefits and NPV, whereas pollen harvesting achieved higher BCR, IRR, profitability index and cumulative ROI, with a shorter simple payback ratio. However, the magnitude and composition of the indicators varied markedly across technologies, reflecting differences in cost structure, revenue composition and risk exposure (Strano et al. 2015; Abdurofi et al. 2021). These indicators describe different aspects of investment performance: absolute benefit, efficiency of capital use and capital recovery. The untrapped system served as the incremental reference; these results do not establish its stand-alone profitability. Pollen harvesting therefore required less additional capital, while venom harvesting offered larger absolute gains conditional on achieving the recorded yields and product prices. Results demonstrated that the financial feasibility indicators collectively indicated that both pollen and bee venom harvesting technologies were economically viable, as they are capable of generating returns well above their respective costs under the prevailing production and market conditions. These results indicate that bee venom harvesting exhibited a high-value but capital-constrained innovation requiring supportive

financing and market structures for successful adoption. Therefore, pollen harvesting offers the most efficient use of invested capital, where moderate initial investment is rapidly recovered through diversified revenue streams.

The results of this study have broader implications for the development of diversified apiculture systems within the emerging global bioeconomy, which emphasises on sustainable utilisation of biological resources to generate economic value while supporting environmental sustainability and rural development. Beekeeping plays a particularly important role in the bioeconomy because it simultaneously contributes to agricultural productivity through pollination services and generating high-value biological products for food, pharmaceutical, and cosmetic industries (Harianja et al. 2023). Moreover, diversifying apiculture systems through integrating pollen and bee-venom production have significantly enhanced the beekeeping economic efficiency by increasing the range of marketable outputs generated from a single biological system (Chandra and Murdyani 2025). Pollen harvesting represented the most economically viable diversification strategy for smallholder beekeepers under the observed conditions in this study. Additionally, bee venom harvesting has significant market potential, its profitability may depend on improvements in production efficiency, technological access, and market development. Strengthening these enabling conditions will be essential for promoting diversified apiculture systems and maximising their contribution to sustainable rural development and the global bioeconomy.

A key strength of this study was the integration of directly measured honey, pollen and bee venom yields with an incremental economic appraisal, enabling assessment of whether additional product revenue compensated for foregone honey, operating costs and technology-specific investment. The inclusion of all three technologies at each of six sites, with the same 18 hives monitored across two harvest periods, supported matched comparisons within districts and accounted for repeated observations. However, unequal accumulation periods also constrained interpretation of seasonal production differences, while the absence of detailed colony-condition and harvesting-efficiency measurements limited explanation of yield variation. Uncertainty regarding market access, saleable product quality and the consistency between venom measurements and the quoted price basis also limits confidence in projected revenue. Finally, the five-year appraisal assumed constant annual yields, real prices and operating costs, making the financial indicators conditional estimates rather than demonstrated long-term returns. Future studies should combine larger, multi-year experiments with verified product measurements, detailed cost records, actual sales data and sensitivity analyses of key production, price and investment assumptions.

Conclusion

This study demonstrates that diversification of smallholder beekeeping through pollen and bee venom harvesting can generate substantial additional economic benefits despite reductions in honey production. Both technologies produced significantly lower honey yields than untrapped hives; however, the additional revenue from pollen and bee venom compensated for the foregone honey and technology-specific investment under the study assumptions. Bee venom harvesting generated the highest annual incremental net benefit and five-year net present value, indicating greater potential for absolute financial returns. In contrast, pollen harvesting required substantially lower additional capital and demonstrated greater investment efficiency and faster capital recovery. These highlight an important economic trade-off between maximising financial returns and ensuring capital affordability among smallholder beekeepers. The results suggest that pollen harvesting represents a more financially accessible diversification option for resource-constrained beekeepers, whereas bee venom harvesting offers greater potential financial gains for those with sufficient investment capital and access to reliable high-value markets. Promoting diversified beekeeping in Tanzania therefore requires improved access to affordable harvesting technologies, technical training, product quality assurance and reliable markets for non-honey bee products. Overall, the findings provide preliminary economic evidence that value-based diversification beyond honey production could strengthen smallholder beekeeping enterprises and contribute to rural livelihood development, provided that investment affordability and market constraints are adequately addressed.

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Author contributions

Ntufye S. Mwakigonja: Conceptualisation, data curation, formal analysis, methodology, writing – original draft, writing – review and editing. **Shibonage K. Mashilingi**: Conceptualisation, methodology, supervision, writing – review and editing. **Samwel M. Limbu**: Conceptualisation, methodology, formal analysis, supervision, writing – review and editing. **Catherine A. Masao**: Conceptualisation, methodology, formal analysis, supervision, funds acquisition, project administration, writing – review and editing. All authors approved the final manuscript for submission.

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Declarations

Conflict of interest

The authors declare that there are no conflicts of interest

Data availability statement The data generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval The study protocol was approved by the Postgraduate Studies Committee (PSC: No. 2021–07-00342) of the University of Dar es Salaam in compliance with the Tanzania Commission of Science and Technology Act of 1986.

Consent to participate Informed verbal consent was obtained from all participating beekeepers before data collection, the method was reviewed and approved by the University of Dar es Salaam.

Consent for publication The authors affirm that human research participants provided informed consent for publication of anonymous quotes.

Code availability Not applicable.

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